

基于SPND响应电流精准计算的压水堆 堆芯功率分布验证实验分析

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摘要 功率分布验证实验是确认堆芯的实际运行功率分布测量值与物理设计软件计算结果一致性的关键环节,可用于评价设计软件的可靠性,也用于评价堆芯实际运行过程与设计预测的一致程度。但是堆芯功率分布实测值的获得依赖于堆内探测器响应信号的计算值。传统的压水堆堆芯物理分析软件计算堆内探测器响应电流的精度不足,直接影响功率分布验证分析的可靠性。本文基于西安交通大学核工程计算物理(Nuclear Engineering Computational Physics, NECP)团队自主研发的压水堆堆芯物理分析软件NECP-Bamboo,开展基于堆内自给能中子探测器(Self-Powered Neutron Detector, SPND)响应电流精准计算的功率分布验证实验分析,定量分析响应电流的精准计算对反应堆功率分布验证结果的贡献。基于AP1000堆芯实际测量数据的验证结果表明,NECP-Bamboo软件计算SPND响应电流的精度显著高于现役AP1000原装专用软件;使用SPND响应电流精准计算值能够有效降低功率分布的误差,NECP-Bamboo软件的误差小于AP1000原装专用软件。

关键词 功率分布验证, AP1000, 自给能中子探测器, NECP-Bamboo

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PWR core power distribution verification experimental analysis based on precisely calculated SPND response current

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Abstract [Background] The power distribution verification experiment is critical to confirm consistency between a reactor core's actual operating power distribution (measured value) and reactor physics design software calculations, as it evaluates both software reliability and alignment between the core's actual operation and design predictions. However, accurate core power distribution measurements rely on in-core detector response signals, and traditional Pressurized Water Reactor (PWR) core physics software lacks sufficient accuracy in calculating Self-Powered Neutron Detector (SPND) response current—this undermines the reliability of power distribution

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verification. **[Purpose]** This study aims to address the inaccuracy of traditional software in SPND response current calculation and its impact on power distribution verification with emphasis on the comparison with that accurately calculated by using NECP-Bamboo (a PWR core physics software independently developed by the NECP team of Xi'an Jiaotong University), and quantitatively analyze how this precise calculation improves power distribution verification results. **[Methods]** Firstly, the actual measurement data from an AP1000 reactor core were collected, including SPND response current and corresponding actual core power distribution data. Then, the NECP-Bamboo was used to calculate the AP1000 core's SPND response current under the same operating conditions, and these values were compared with the measured data to assess the software's accuracy. Subsequently, the core power distribution was derived using NECP-Bamboo's calculated SPND response current following standard procedures. Finally, statistical indicators, i.e., root mean square error, relative error, were used to quantitatively compare errors between the two software. **[Results]** Based on the AP1000 core's actual measurement data, the verification results show clear advantages of NECP-Bamboo: its accuracy in calculating SPND response current is significantly higher than that of the original dedicated software; using its precisely calculated SPND response current effectively reduces core power distribution verification errors; and its power distribution error is consistently smaller than that of the original software. **[Conclusions]** Results of this study confirm that NECP-Bamboo outperforms the in-service AP1000 original dedicated software in SPND response current calculation for PWR cores; its precise SPND response current calculation directly reduces reactor power distribution verification errors, enhancing the reliability of results. It indicates that NECP-Bamboo can serve as a reliable tool for PWR core physics analysis and power distribution verification in engineering practice.

Key words Power distribution verification, AP1000, Self-powered neutron detector (SPND), NECP-Bamboo

功率分布是堆芯运行状态的重要反映以及确定堆芯运行限值和安全裕量的关键参数,其验证实验可以反映堆芯物理分析软件的可靠程度,也用于评价堆芯实际运行过程与设计预测的一致程度。现有功率分布验证实验是将计算软件给出的功率分布计算值与功率分布实测值对比,判断误差是否满足工业限值要求。

以 AP1000 为例,需要先利用 AP1000 原装专用软件计算获得堆芯功率分布计算值与堆内自给能中子探测器(Self-Powered Neutron Detector, SPND)响应电流计算值,随后利用该软件结合 SPND 电流实测值,基于样条函数拟合法,计算获得堆芯功率分布重构值,作为堆芯功率分布的实测值。

现有功率分布验证实验的可靠程度依赖于设计软件的 SPND 响应电流计算精度^[1]。因此,本文基于能精准计算堆内 SPND 响应电流的压水堆堆芯分析软件 NECP-Bamboo,定量分析响应电流的精准计算对 AP1000 机组堆芯功率分布验证的影响。

1 AP1000堆芯建模计算

NECP-Bamboo 是西安交通大学核工程计算物理 (Nuclear Engineering Computational Physics, NECP) 团队自主研发的压水堆堆芯物理分析软件^[2], 该软件采用改进两步法技术^[3], 主要由栅格计算程序 Bamboo-Lattice^[4]、堆芯稳态计算程序

Bamboo-Core^[5]、瞬态计算程序 Bamboo-Transient^[6]、自动建模程序 Bamboo-Frame^[7]和乏燃料组件核素成分分析程序 Bamboo-SFuel^[8]5 部分组成, 已经过大量核电厂实测数据的验证与确认^[9-11]。

AP1000 反应堆由 157 个 17×17 的燃料组件组成,满功率为 3 400 MW^[12]。径向上,共使用 5 类不同富集度的燃料组件,布置了 48 个钒 SPND(如图 1 所示)。轴向上,活性区范围内共有 8 个定位格架和

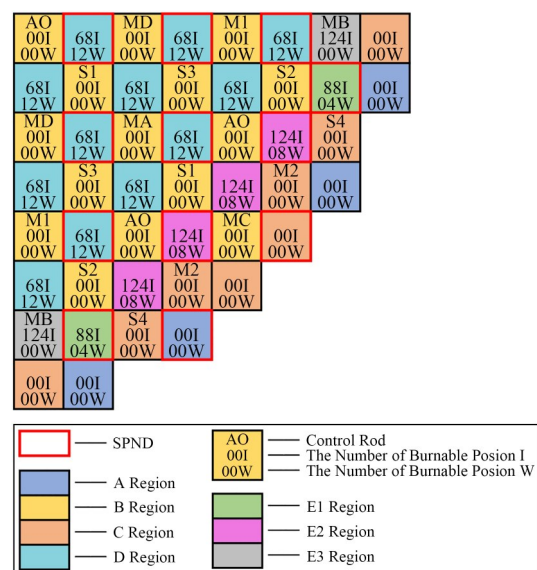


图1 AP1000堆芯径向组件布置(彩图见网络版)
Fig.1 Radial assembly layout of AP1000 (color online)

4个中间搅混格架,均进行显式建模。全堆芯共计算了92种燃料栅格(格架的显式建模会增加栅格类型数)、20种反射层栅格,堆芯计算中,径向上每个组件划分为 2×2 个节块,轴向上划分了44层网格。AP1000堆芯中使用的钚 SPND 具有三层同轴圆环形几何结构,从内到外依次为发射极、绝缘层和收集极。

2 SPND 响应电流计算

2.1 SPND 响应电流计算模型

NECP-Bamboo 可以计算得到不同时间响应特性的缓发和瞬发电流组分,具备精确的 SPND 响应电流计算能力^[13-17]。该软件先通过 Bamboo-Lattice 栅格模拟结合 SPND 精细燃耗计算,获得堆芯在不同燃耗深度下各组件及探测器的相关参数(少群常数、均匀化截面)与发射体核素构成。针对各堆芯状态,采用基于电流连续性方程的计算确定电子逃逸概率和瞬发灵敏度系数^[17];按照状态矩阵设置,进而拟合构建少群常数库。堆芯计算时,库数据用于在线插值,获取当前状态的电子逃逸概率和瞬发灵敏度系数。基于此,分别计算缓发电流(涉及放射性活度)和瞬发电流(利用中子通量密度),得到不同时间特性的电流组分^[14,18]。整体计算流程如图2所示。

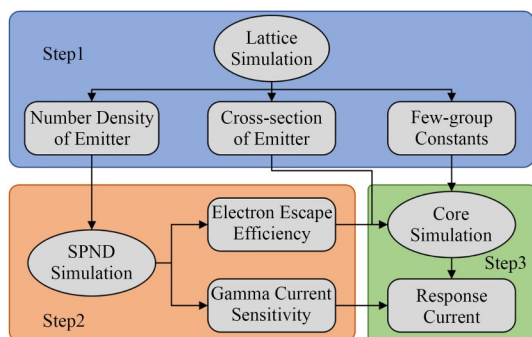


图2 SPND 电流模拟计算流程图

Fig.2 Simulation flowchart for SPND current

总电流的计算公式如下:

$$I = I_{\text{delay}} + I_{\text{prompt}} = q \sum_i A_i \varepsilon_{ti} + S \phi_{\text{SpND}}^{\text{het}} F_{\text{emi}} V \quad (1)$$

式中: I 为 SPND 总响应电流; $A_i I_{\text{delay}}$ 为 SPND 缓发电流; $A_i I_{\text{prompt}}$ 为 SPND 瞬发电流; $A_i q$ 为电荷常数,值为 1.602×10^{-19} C; A_i 为核素 i 的放射性活度, s^{-1} ; ε_{ti} 为核素 i 的电子逃逸概率,是指电子从发射极产生电子成功逃逸出发射极并被收集极捕获的比例^[14,18]; S 为瞬发电流灵敏度系数,是指单位中子通量所产生的瞬发电流值^[14,18], $\text{A} \cdot \text{cm}^{-1} \cdot \text{s}$; $\phi_{\text{SpND}}^{\text{het}}$ 为 SPND 发射体中子通量密度, $\text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$; F_{emi} 为 SPND 发射体通量形

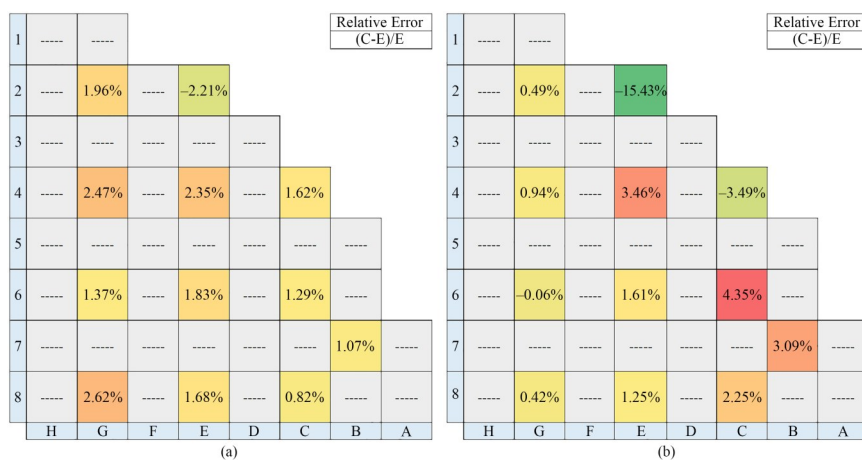
状因子,由栅格计算获得; V 为 SPND 发射体体积^[14,18], cm^3 。 ε_{ti} 与 S 均基于电流连续性方程通过蒙卡程序进行电子输运计算获得^[17]。

其中瞬发电流主要由伽马光子与 SPND 相互作用(光电效应、康普顿效应以及电子对效应)产生,伽马光子主要来源于中子俘获反应以及裂变反应,由于上述反应时间极短,因此瞬发电流大小可以直接反映堆内中子通量水平大小。缓发电流来源于发射极材料的核素俘获中子后形成的不稳定核素。这些核素随后大多以 β^- 衰变的形式释放一个电子、一个反电子中微子和一个不稳定的末态核素。此时探测器的响应时间由 β^- 衰变的半衰期决定,半衰期可能从几秒到几分钟不等,这部分电流被称为中子缓发电流。

2.2 SPND 响应电流计算结果

使用软件对 AP1000 堆芯进行了跟踪模拟计算^[19],选择了具有实测结果的6个燃耗点。图3~8依次为 9 764.6 MWd·tU⁻¹、11 271.7 MWd·tU⁻¹、12 642.5 MWd·tU⁻¹、15 132.3 MWd·tU⁻¹、16 214.8 MWd·tU⁻¹和 16 687.5 MWd·tU⁻¹ 6个具有实测结果的燃耗状态下 NECP-Bamboo 和 AP1000 原装专用软件两个软件的 SPND 响应电流计算值与实测值的误差,最正、最负及均方根(Root Mean Square Error, RMS)误差统计结果如表1所示。可以发现,1)NECP-Bamboo 与 AP1000 原装专用软件的计算误差分布趋势一致;2)燃耗深度加深时,NECP-Bamboo 的计算结果误差基本不变,AP1000 原装专用软件的最负误差逐渐增大;3)NECP-Bamboo 的均方根误差均小于 AP1000 原装专用软件。

两个程序在误差变化趋势上的差异可通过其计算模型的特性进行解释:一方面,NECP-Bamboo 程序在堆芯实际运行过程中能够动态获取不同燃料组件在各堆芯状态下的 SPND 响应特性参数;另一方面,NECP-Bamboo 程序采用微观燃耗计算方法直接精确求解发射体核素组成,从而获得高精度的响应电流计算结果,其误差波动范围较小。而相比之下,AP1000 原装专用软件程序由于采用吸收反应率等效于放射性活度的理论假设,且未对瞬发与缓发信号组分进行区分,在运行过程中仅通过经验修正系数实施校正^[3];这种处理方式无法完整表征堆芯状态的动态演变,需要对所有类型燃料组件采用统一的灵敏度系数,随着堆芯运行过程中功率历史复杂度的提升,经验修正系数的适用性逐渐减弱,最终导致其计算误差呈现显著增大的趋势。

图3 AP1000堆芯SPND响应电流计算误差($Bu=9\,764.6\text{ MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)

(a) NECP-Bamboo软件, (b) AP1000 原装专用软件

Fig.3 Calculation error of SPND response current in AP1000 ($Bu=9\,764.6\text{ MWd}\cdot\text{tU}^{-1}$) (color online)
(a) NECP-Bamboo, (b) Original dedicated software for AP1000图4 AP1000堆芯SPND响应电流计算误差($Bu=11\,271.7\text{ MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)

(a) NECP-Bamboo软件, (b) AP1000 原装专用软件

Fig.4 Calculation error of SPND response current in AP1000 ($Bu=11\,271.7\text{ MWd}\cdot\text{tU}^{-1}$) (color online)
(a) NECP-Bamboo, (b) Original dedicated software for AP1000图5 AP1000堆芯SPND响应电流计算误差($Bu=12\,642.5\text{ MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)

(a) NECP-Bamboo软件, (b) AP1000 原装专用软件

Fig.5 Calculation error of SPND response current in AP1000 ($Bu=12\,642.5\text{ MWd}\cdot\text{tU}^{-1}$) (color online)
(a) NECP-Bamboo, (b) Original dedicated software for AP1000

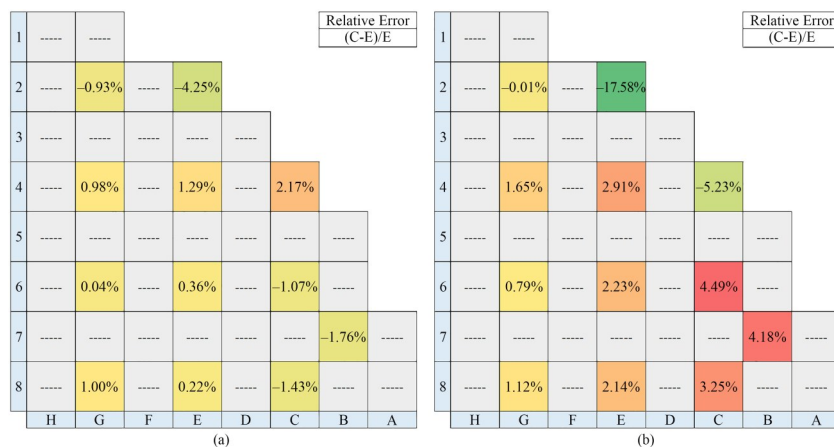


图6 AP1000堆芯 SPND 响应电流计算误差($Bu=15\ 132.3\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
(a) NECP-Bamboo 软件, (b) AP1000 原装专用软件

Fig.6 Calculation error of SPND response current in AP1000 ($Bu=15\ 132.3\ \text{MWd}\cdot\text{tU}^{-1}$) (color online)
(a)NECP-Bamboo, (b) Original dedicated software for AP1000

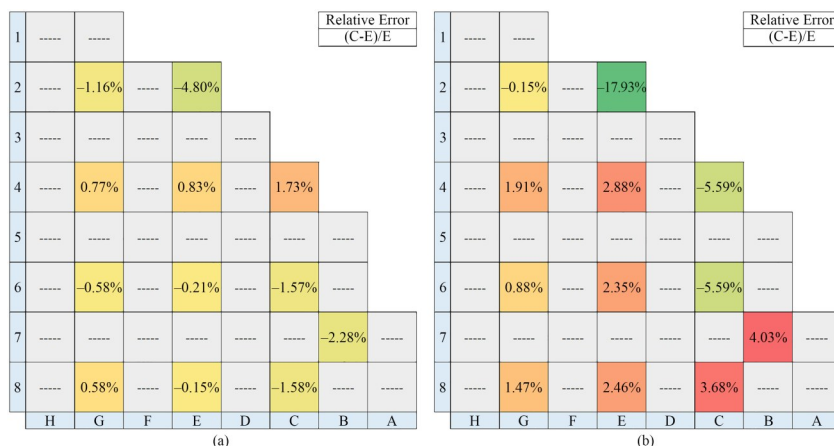


图7 AP1000堆芯 SPND 响应电流计算误差($Bu=16\ 214.8\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
(a) NECP-Bamboo 软件, (b) AP1000 原装专用软件

Fig.7 Calculation error of SPND response current in AP1000 ($Bu=16\ 214.8\ \text{MWd}\cdot\text{tU}^{-1}$) (color online)
(a) NECP-Bamboo, (b) Original dedicated software for AP1000

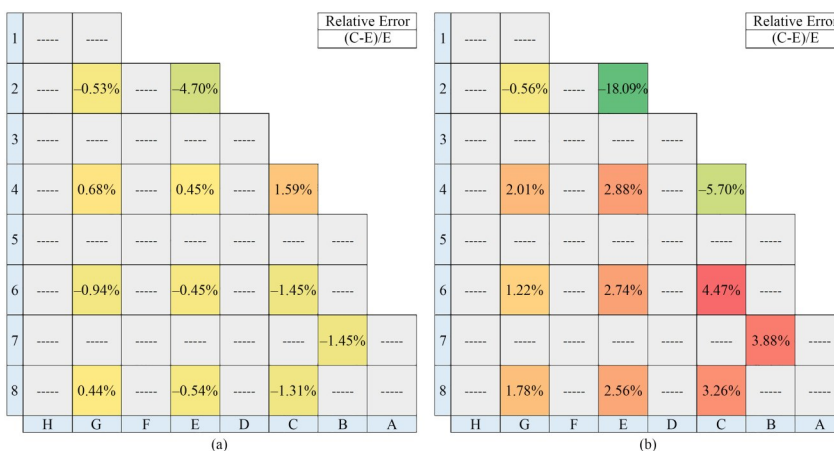


图8 AP1000堆芯 SPND 响应电流计算误差($Bu=16\ 687.5\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
(a) NECP-Bamboo 软件, (b) AP1000 原装专用软件

Fig.8 Calculation error of SPND response current in AP1000 ($Bu=16\ 687.5\ \text{MWd}\cdot\text{tU}^{-1}$) (color online)
(a) NECP-Bamboo, (b) Original dedicated software for AP1000

表1 AP1000堆芯SPND响应电流计算误差极值统计
Table 1 Statistics of extreme values and calculation errors of SPND response current in AP1000

燃耗深度 Burnup depth / MWd·tU ⁻¹	NECP-Bamboo			AP1000 原装专用软件 Original dedicated software for AP1000		
	最正误差 Max positive error / %	最负误差 Max negative error / %	RMS / %	最正误差 Max positive error / %	最负误差 Max negative error / %	RMS / %
9 764.6	2.62	-2.21	1.86	4.35	-15.43	5.01
11 271.7	2.79	-2.48	1.57	4.35	-16.24	5.29
12 642.5	1.76	-3.27	1.38	4.37	-16.64	5.44
15 132.3	2.17	-4.25	1.68	4.49	-17.58	5.83
16 214.8	1.73	-4.80	1.82	4.03	-17.93	6.06
16 687.5	1.59	-4.70	1.66	4.47	-18.09	6.04

3 功率分布验证

$$P_{\text{rec}}(r) = \frac{I_{\text{mea}}(r)}{I_{\text{pre}}(r)} \cdot P_{\text{pre}}(r) \quad (3)$$

3.1 功率分布验证方法

本文基于压水堆功率分布在线监测程序NECP-ONION^[20],采用样条函数法进行堆芯功率重构计算,该方法的基本思想是假设堆芯功率分布重构值与预测值之比等于探测器信号测量值与预测值之比,即:

$$\frac{P_{\text{rec}}(r)}{P_{\text{pre}}(r)} = \frac{I_{\text{mea}}(r)}{I_{\text{pre}}(r)} \quad (2)$$

式中: $P_{\text{rec}}(r)$ 为相对功率重构值; $P_{\text{pre}}(r)$ 为相对功率预测值; $I_{\text{mea}}(r)$ 为响应电流实测值; $I_{\text{pre}}(r)$ 为响应电流预测值,A。堆芯中的重构功率可以表示为:

3.2 功率分布验证结果

图9~14给出了NECP-Bamboo软件的计算功率分别与NECP-Bamboo和AP1000原装专用软件重构实测功率分布的验证结果。图15汇总了各燃耗点的最大正误差、最大负误差及均方根误差,AP1000原装专用软件在图中用AP1000代表。从式(3)中可以看出,功率重构值与探测器信号测量值和预测值的比值呈正相关,响应电流的计算误差将直接影响到功率重构值的精度。因此,NECP-Bamboo软件的SPND响应电流精准计算能显著降低功率分布验证结果的误差。

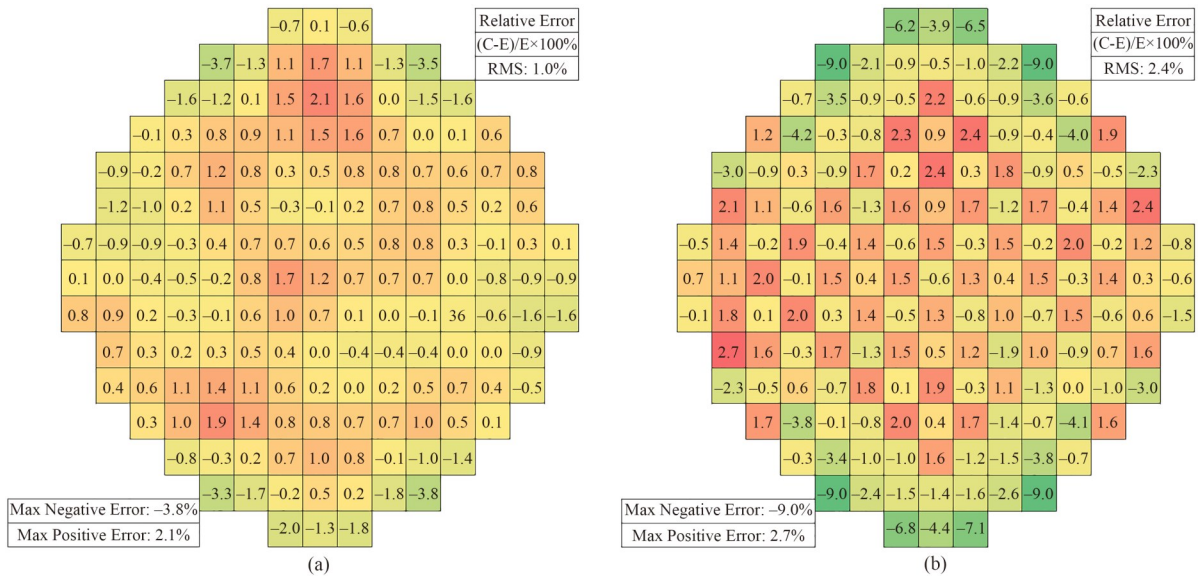


图9 NECP-Bamboo计算功率分布与实测功率分布的误差(Bu=9 764.6 MWd·tU⁻¹)(彩图见网络版)
(a) 实测值基于NECP-Bamboo响应电流计算值,(b) 实测值基于AP1000原装专用软件响应电流计算值
Fig.9 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution (Bu=9 764.6 MWd·tU⁻¹) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

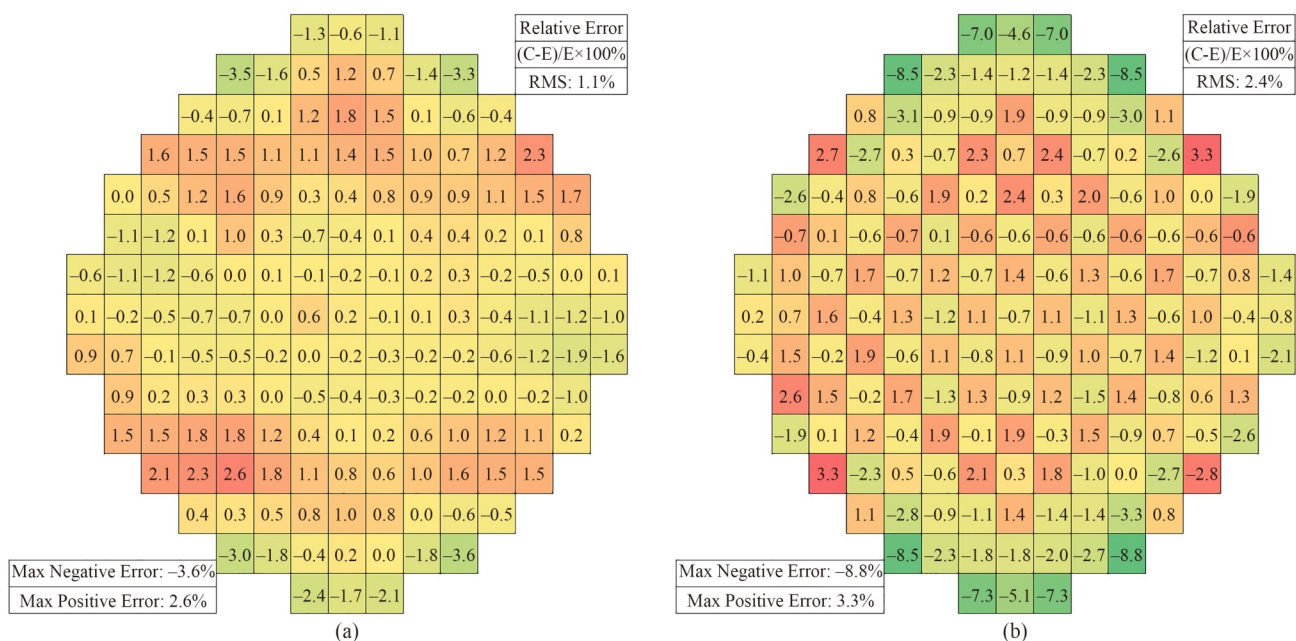


图 10 NECP-Bamboo 计算功率分布与实测功率分布的误差 ($Bu=11\ 271.7\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
 (a) 实测值基于 NECP-Bamboo 响应电流计算值, (b) 实测值基于 AP1000 原装专用软件响应电流计算值
Fig.10 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution ($Bu=11\ 271.7\ \text{MWd}\cdot\text{tU}^{-1}$) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

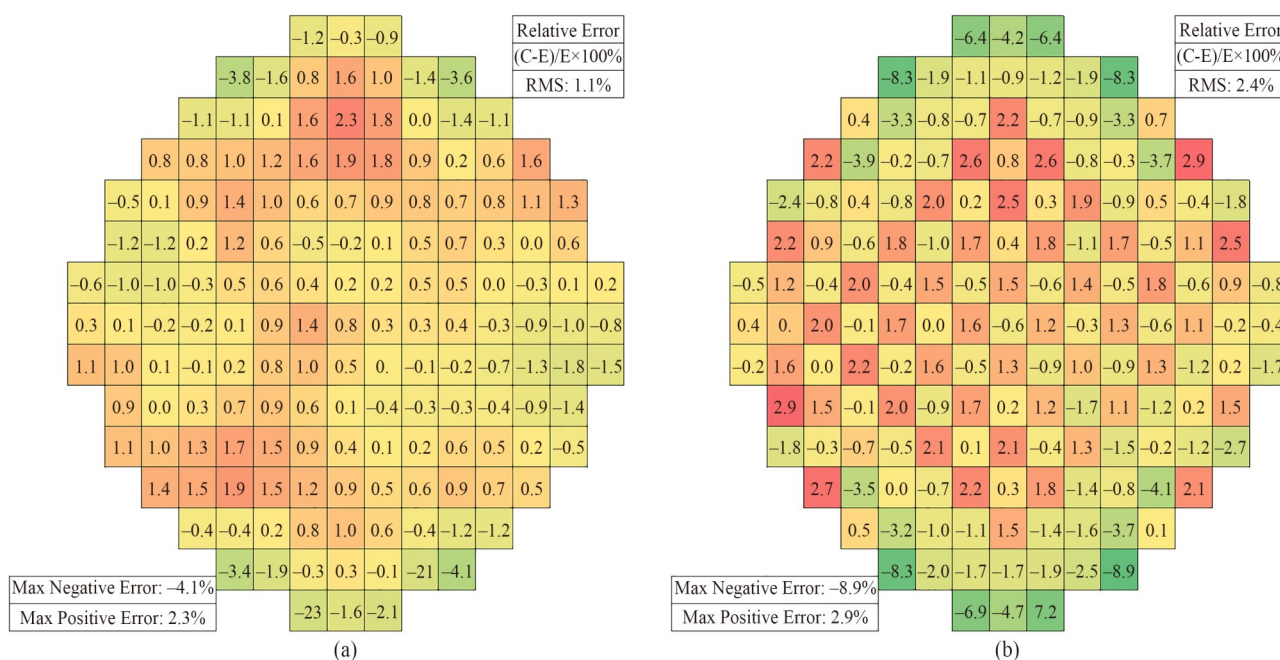


图 11 NECP-Bamboo 计算功率分布与实测功率分布的误差 ($Bu=12\ 642.5\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
 (a) 实测值基于 NECP-Bamboo 响应电流计算值, (b) 实测值基于 AP1000 原装专用软件响应电流计算值
Fig.11 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution ($Bu=12\ 642.5\ \text{MWd}\cdot\text{tU}^{-1}$) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

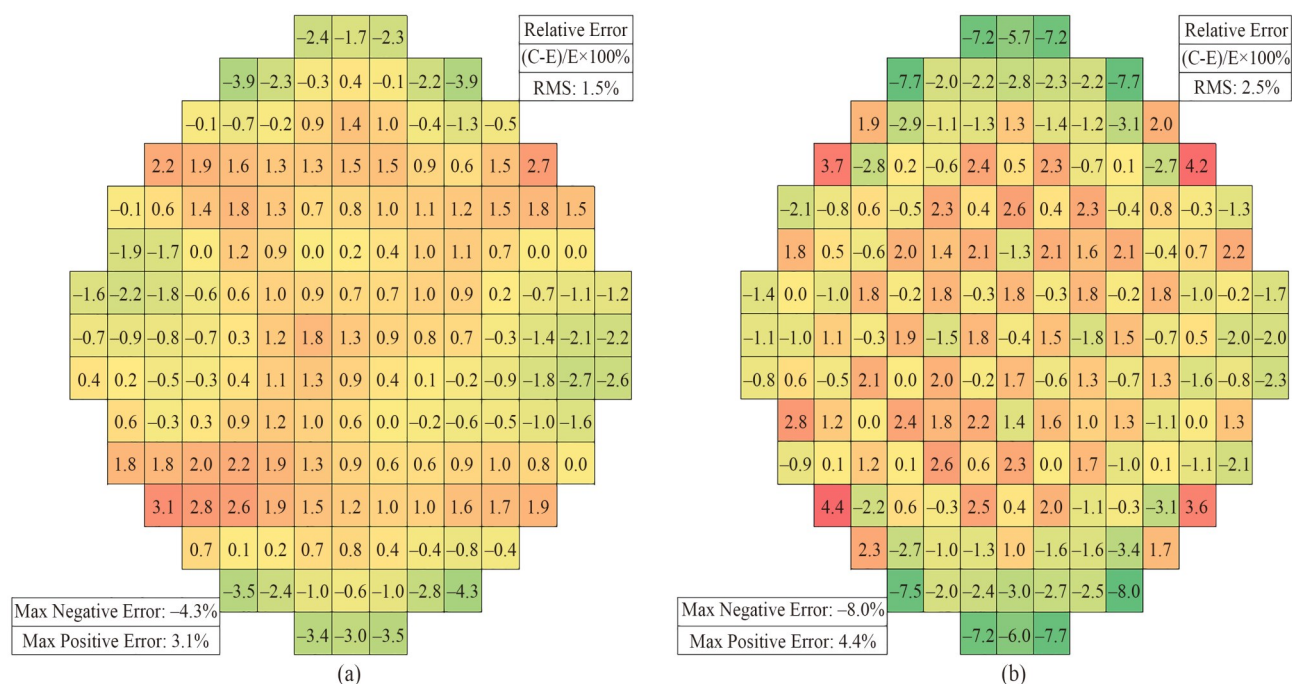


图 12 NECP-Bamboo 计算功率分布与实测功率分布的误差 ($Bu=15\ 132.3\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
 (a) 实测值基于 NECP-Bamboo 响应电流计算值, (b) 实测值基于 AP1000 原装专用软件响应电流计算值
Fig.12 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution ($Bu=15\ 132.3\ \text{MWd}\cdot\text{tU}^{-1}$) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

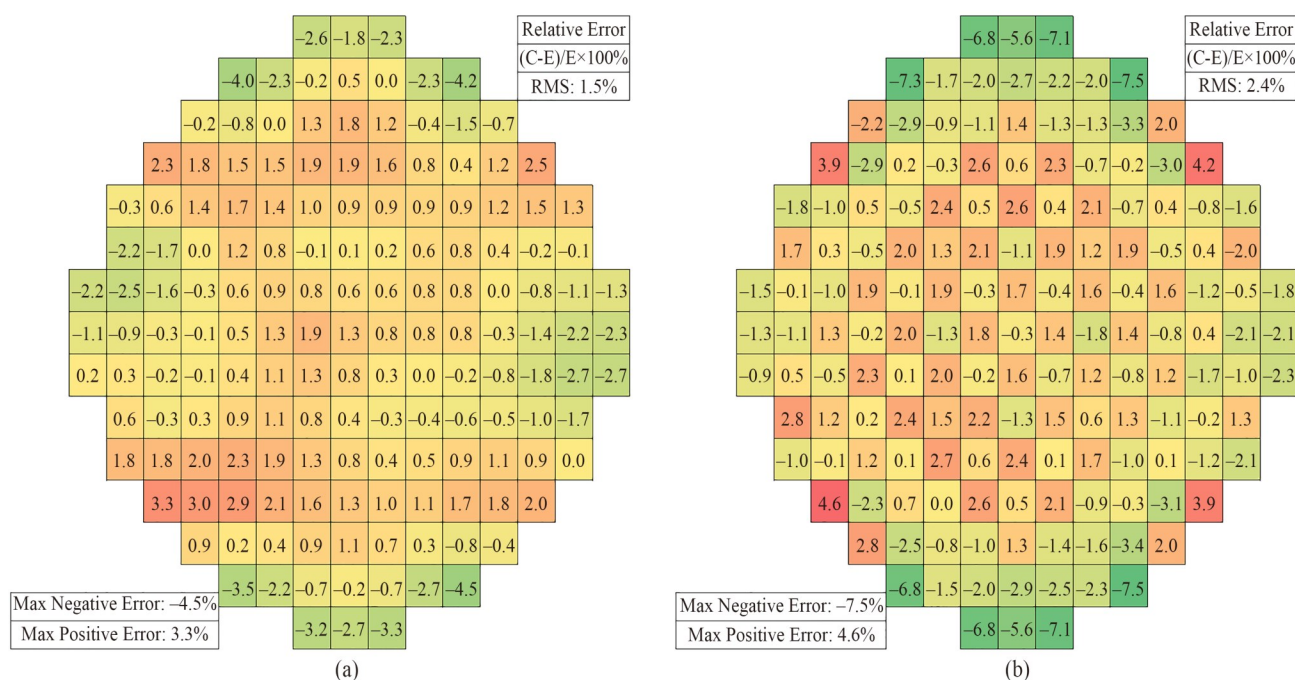


图 13 NECP-Bamboo 计算功率分布与实测功率分布的误差 ($Bu=16\ 214.8\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)
 (a) 实测值基于 NECP-Bamboo 响应电流计算值, (b) 实测值基于 AP1000 原装专用软件响应电流计算值
Fig.13 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution ($Bu=16\ 214.8\ \text{MWd}\cdot\text{tU}^{-1}$) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

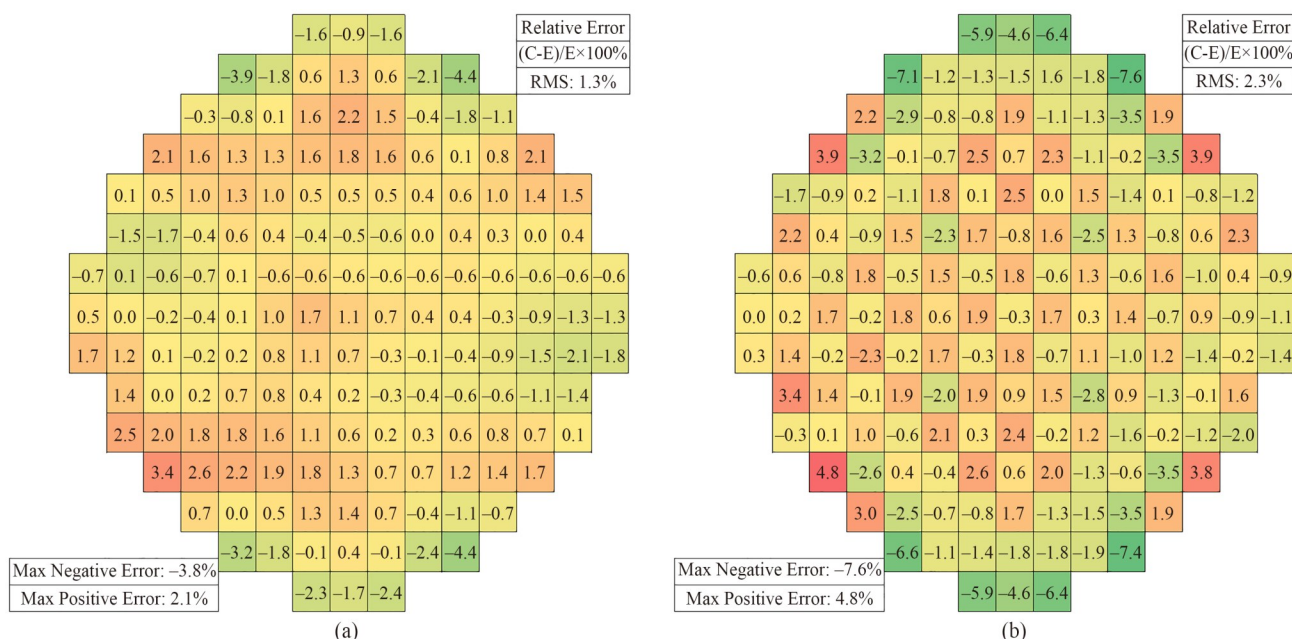


图 14 NECP-Bamboo 计算功率分布与实测功率分布的误差 ($Bu=16\ 687.5\ \text{MWd}\cdot\text{tU}^{-1}$) (彩图见网络版)

(a) 实测值基于 NECP-Bamboo 响应电流计算值, (b) 实测值基于 AP1000 原装专用软件响应电流计算值

Fig.14 The error between the power distribution calculated by NECP-Bamboo and the measured power distribution ($Bu=16\ 687.5\ \text{MWd}\cdot\text{tU}^{-1}$) (color online) (a) The measured value based on the calculated value of NECP-Bamboo, (b) The measured value based on the calculated value of the original dedicated software for AP1000

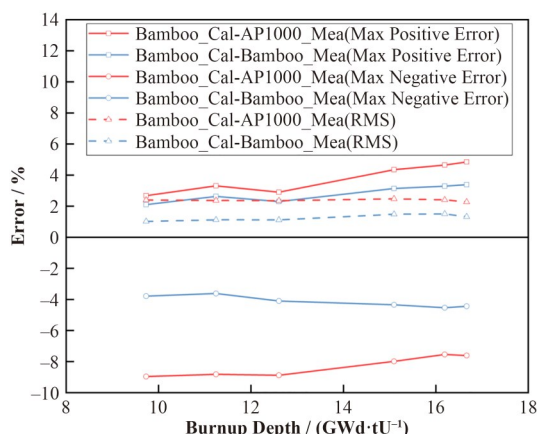


图 15 各燃耗点的功率分布误差 (彩图见网络版)

Fig.15 Power distribution errors of each burnup depth (color online)

4 结语

本文基于 SPND 响应电流的精准计算对 AP1000 机组反应堆的功率分布验证实验进行分析。结果表明, NECP-Bamboo 软件计算 SPND 响应电流的精度显著高于现役 AP1000 原装专用软件; 使用 SPND 响应电流精准计算值能够有效降低功率分布的误差, NECP-Bamboo 软件的误差小于 AP1000 原厂专用软件。未来将在 HPR1000 等不同类型的反应堆中继续验证本文提出的 SPND 响应电流计算模型。

作者贡献声明 杜思芃负责模型优化设计、结果分析和文章撰写; 李云召负责理论指导、文章修改和终稿校订; 周克峰负责指导并提供支持; 张航冀负责编写代码和整理结果; 邵睿智负责建立 SPND 响应电流计算模型; 曹良志负责技术指导和提供研究经费等。

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