Contribution ID: **95** Type: 口头报告

局部高空泡板型燃料压水堆高保真核热耦合计算方法

摘要

由于具有高传热效率与高功率密度，板式燃料元件已在研究堆和特殊应用领域获得广泛应用。随着对更高反应堆堆芯功率密度的追求不断推进，即便在压水堆中，也会出现局部高空泡现象。此时，堆芯内部存在紧密耦合的多物理过程，如中子学与两相流热工水力等。仅使用中子学或热工水力单独计算，难以得到最准确的评价结果。然而，目前尚无可同时考虑上述复杂耦合机制的反应堆堆芯耦合计算程序，这限制了板式燃料元件进一步提升功率密度。为了解决这一问题，本论文基于蒙卡程序 RMC 和商业 CFD 软件 ANSYS Fluent，建立了适用于高功率密度 PWR 堆芯且考虑局部高空泡份额的精细化稳态核热耦合计算方法。本文选取由中国核动力研究设计院提出的 COPHP（Coupling calculation Of plate-type PWR based on High Parameters）基准题，分析了所提出耦合计算方法的数值收敛特性，结果显示耦合计算在单相与两相工况下均在五步迭代内收敛。对从 0% 到 100% 满功率的 6 种不同功率水平进行了计算与分析。结果表明，在满功率工况（HFP）下，流道内最大出口汽泡份额可达 0.48，远高于传统压水堆。在功率水平变化的过程中，堆芯经历从单相工况到两相工况的转变。在 HFP 条件下，包壳表面的最大局部热流密度高达 918.49 kW/m²，为堆芯平均热流密度的 2.33 倍。本文提出的耦合计算方法对高功率密度板式 PWR 的堆芯设计与安全分析具有指导意义。

关键词

高功率密度压水堆；局部高空泡；蒙卡；两相流；核热耦合

Abstract

Due to the high heat transfer efficiency and power density, plate-type fuel elements have been widely applied in research reactors and special application scenarios. As the pursuit of higher reactor core power density continues, even in PWR, high local void fraction phenomena will occur. At this point, there is a tight multi-physics coupling within the reactor core, such as neutronics and two-phase flow thermohydraulics, making it impossible to obtain the most accurate evaluation results with standalone neutronic or thermohydraulic calculations. However, currently, no reactor coupling calculation code considers the complex coupling mechanisms mentioned above. Thus, this limits the further increase in power density of plate-type reactors. To address this issue, this paper establishes a refined steady-state Neutronic-Thermohydraulic (N-TH) coupling calculation method suitable for the core of high-power density PWRs based on the RMC and the commercial CFD software ANSYS Fluent. Coupling calculation Of plate-type PWR based on High Parameters (COPHP) problem pro-posed by Nuclear Power Institute of China (NPIC) is selected to show the numerical convergence characteristics of the coupling calculation method. It achieves convergence within five iterations under both single-phase and two-phase operating conditions. Calculations and analyses were carried out for 6 different power levels ranging from 0% to 100%. The results show that under the Hot Full Power (HFP) condition, the maximum outlet void fraction in sub-channels reached 0.48, significant-ly higher than that of traditional PWRs. As the power level changes, there is a transition from single-phase operating mode to two-phase operating mode. Under HFP condition, the maximum local heat flux on the cladding surface reached 918.49 kW/m2, which is 2.33 times that of the average heat flux of the core. The coupled calculation code developed in this paper has guiding significance for the design and safety analysis of high-power density plate-type PWRs.

Keywords

High-power density reactor; High local void fraction; Monte Carlo; Two-phase flow; N-TH coupling calculation

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Session Classification: 核能科学与工程

Track Classification: 03 口头报告: 核能科学与工程