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Axial 3D effect on modeling a heterogeneous core

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ABSTRACT

To assess the need of next generation method (NGM) for analyzing heterogeneous cores, a mini-core with 6×6 boiling water reactor (BWR) bundles is proposed as a benchmark problem. It is found that the traditional method based on reflective single bundle homogenization leads to very large errors even for a sliced 2D core analysis. For the 3D case there is very strong axial interface effect on fine mesh scale that has nothing to do with axial homogenization and cannot be captured by the traditional coarse mesh nodal method with radial pin power reconstruction. A single bundle 3D homogenization and pin power reconstruction model is proposed to couple with coarse mesh nodal method such that the detailed 3D effect of the reference solution can be reproduced accurately.

1. Introduction

Advanced core and fuel assembly designs of light water reactor (LWR) have been developed to improve operational flexibility, economic performance and to further enhance safety features of nuclear power plants. Strong heterogeneous fuel loading, both radially and axially, brings challenge to reactor analysis methods that are currently widely implemented. Although some improvements have been introduced to the traditional methods to address the challenge (Zhang et al., 2012; Bahadir and Lindahl, 2009), however, 2D reflective single bundle homogenization and 3D coarse mesh nodal methods are still maintained. It has been recognized that the use of pre-generated cross-section table based on the reflective single assembly homogenization model is a major drawback to address the challenge.

Recent NGM research introduced methods completely different from the traditional ones, giving up the use of reflective single assembly homogenization. The SCOPE2 code performs whole core pin-by-pin calculation using pre-generated homogenized cell cross sections (Tatsumi et al., 2010). While the nTracer code uses homogenized cell cross sections generated on-the-fly instead of pre-generated ones (Sang and Joo, 2011). These NGM solvers can handle highly heterogeneous assembly appropriately, although still using coarse axial nodes. Its practical efficiency issues are not fully resolved yet despite the use of the effective CMFD acceleration method. However in this paper we find that there is strong 3D effect near the axial interfaces of sections of different composition, which has nothing to do with axial homogenization. To account for the 3D effect it is not only necessary to use cell meshes in the radial direction but fine axial meshes near the interfaces as well.

In this paper a 3D BWR mini-core problem is designed to investigate the NGM issues and to compare the various methods. We first analyze why the traditional method is not adequate for analyzing the BWR mini-core problem, which is highly heterogeneous in both radial and axial directions. Based on the finding of the root cause, a non-reflective single bundle 3D homogenization and pin power reconstruction model is proposed which when coupled to the coarse mesh nodal method can reproduce the detailed 3D effect of the reference solution accurately.

Section 2 describes the configuration and key features of the mini-core problem. Section 3 discusses the methodology used to generate the reference solution of the mini-core problem. The reference solution is not generated with rigorous 3D heterogeneous transport calculation, which would be very difficult to do. Instead the reference solution is obtained with the simplified 3D fine-mesh diffusion calculation, which nevertheless retains all the important physics effects and mathematical characters of the solution. The reference solution captures the major 3D heterogeneity effects that we are interested in. Section 4 shows the large error of the traditional method in analyzing this mini-core problem and therefore introduces the 3D single bundle homogenization model to overcome the problem. Different from the traditional 2D reflective single bundle homogenization method, the new model is 3D and non-reflective. Since 3D coarse mesh nodal method is still used for the whole core simulation in this work, an appropriate 3D pin power reconstruction method is also proposed to calculate the final pin power distribution. Section 5 shows all the numerical results of analyzing the mini-core benchmark problem with the proposed 3D homogenization to resolve the axial 3D effect problem. Section 6 concludes the paper.

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2. BWR mini-core problem specification

BWR fuel and core design are more complicated than that of PWR. A BWR bundle has a large water hole in its center and has variable enrichment in its pin composition. In the axial direction, there are some partial length fuel rods. Besides, the variation of coolant density along the fuel channel is very severe. Fig. 1 shows the (approximate) radial fuel design of a BWR fuel bundle. The central square cells without fuel pins form the moderator region. The dark blue zone outside the fuel is the bundle box, with the wide water gap on the upper and left sides and the narrow water gap on the lower and right sides. The control blade will be inserted into the wide gap. The fuel pins are of different enrichment and of different gadolinium content. The fuel pins in red or pink are part length pins. There are five different coolant density values varying axially from 0.763 g/cm^3 on the bottom to 0.1878 g/cm^3 on the top.

Fig. 2 depicts the quarter core radial layout of the BWR mini-core problem. There are 2 types of fuel bundles. Bundles in blue (I, II and IV) are fresh fuel, while the ones in red (III, V and VI) are burnt fuel with average burnup of 20GWd/MTU. Two sets of control blades (in black) are inserted in the quarter core. There is a radial water reflector with thickness of one bundle pitch, and vacuum boundary condition is assumed at the outer boundary.

The axial core configuration is depicted in Fig. 3, with the coolant density variation shown as well. Part (a) in Fig. 3 shows the axial view of the core cut along the line PP' in Fig. 2, where different color of the fuel denotes different fuel burnup. Both sets of control blade are partially inserted. The control blade upper tip positions

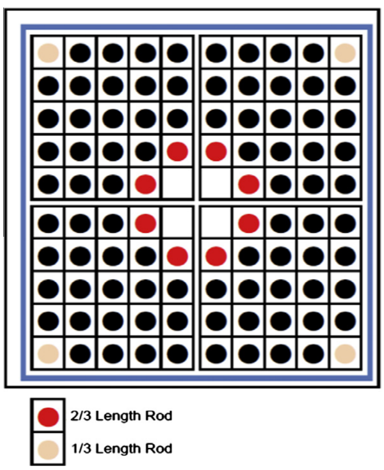

Fig. 1. Radial pin layout of the BWR bundle.

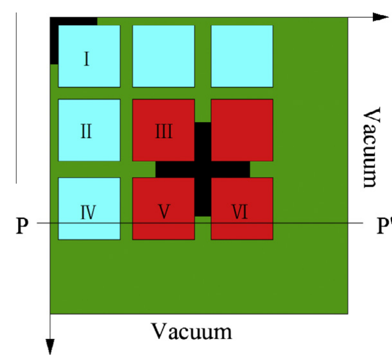

Fig. 2. Quarter core radial configuration.

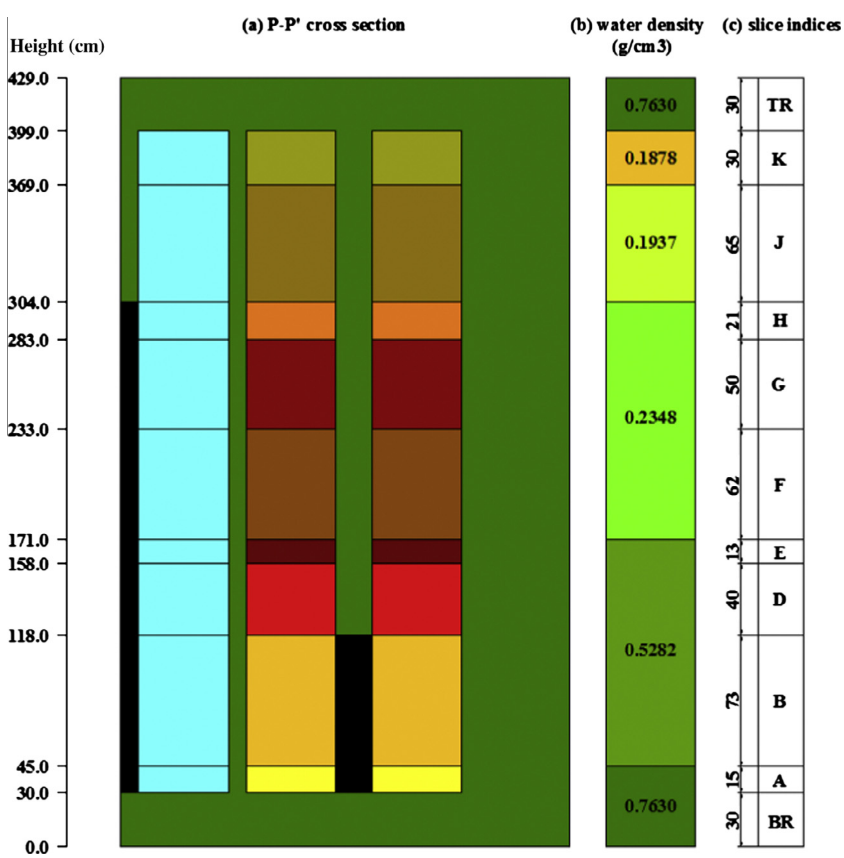

Fig. 3. Axial core configuration.