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Improvement in the simulation of detector readings using a high fidelity local flux reconstruction-based method

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ABSTRACT

Even with current computing capabilities, detailed full core three-dimensional (3-D) transport calculations are still not practical. However, if we are satisfied with knowing only the average values of spatial flux distributions, the 3-D diffusion solution will constitute the final solution. On the other hand, in reactor design and safety analysis, direct information about the local flux distribution for the heterogeneous assemblies is required to assess the design and determine the safety margins. For this reason, after having solved the full-reactor-core problem, we have to look into the possibilities of recovering in a second step the information on local properties of single heterogeneous assemblies. In particular, the detector readings at detector locations are derived using these global homogenized parameters by applying appropriate numerical methods such as advanced interpolations. In this paper, we propose a method based on flux reconstruction to calculate the simulated detector readings in three-dimensions with high fidelity. Data from detector readings are very important in ensuring optimal reactor operations as well as in detecting any deviations from normal operations. Thus, calculating the detector readings with high fidelity will allow improvements to operating and safety margins. To validate this method, comparisons between detector reading simulation results and measurements from an operating CANDU reactor will be conducted and results will be presented.

1. Introduction

The use of homogenized parameters to predict reactor properties results in an inevitable loss of fine-structure information, which would otherwise be available if the reactor were analysed by methods not involving homogenization. However, a reactor may contain several hundred fuel assemblies (channels), and each assembly/channel may include several hundred fuel pins. Hence, an explicit representation of heterogeneous assemblies requires tens of thousands of different regions making full core three-dimensional (3-D) transport calculations impractical. However, by combining the global reactor core flux distribution from a diffusion theory computation with a local fuel bundle flux distribution from a transport theory computation, much of the detailed heterogeneous flux distribution across the reactor core may be recovered. This method is referred to as flux reconstruction. This method is able to provide much more local flux distribution detail than using diffusion theory computations alone. Current topics in reactor core simulation often require this detail. One such current topic is the flux reconstruction of simulated detector readings. Since the source of the flux information within the core of a real operating reactor is based entirely on detector signals, with most of these detector signals being direct measurements of the neutron flux, the flux reconstruction of simulated detector readings carries a high importance in terms of preparing a reactor core simulation that is effective in matching the reactor-core neutronics of the real reactor. The mechanics of the flux reconstruction method and its use in generating simulated detector readings is based on advanced methods of interpolation. In this paper we present the method itself (Dahmani et al., 2010,Dahmani et al., 2011, Cho et al., 2000, Boer and Finnemann, 1985, Rempe et al., 1988, and Lee et al., 2002) plus the application of the method in generating simulated travelling flux detector scan (TFD scan) signals, and comparison of these simulated detector signals with measured signals from a real operating reactor. This paper is structured as follows. Section 2 provides a brief description of the common standard interpolation methods used to calculate the fluxes at detector locations. In Section 3, the proposed method, based on flux reconstruction, for calculating the fluxes at detector locations is described. Some discussions on the results are presented in Section 4, where comparisons between the simulated flux at detector locations using both standard and new methods are provided. Section 5 concludes the paper with some closing remarks.

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2. Overview of the current methods for calculating flux at detector locations

Nuclear reactor core diffusion codes typically use interpolation of the mesh flux in all 3 dimensions to generate simulated detector readings. The simplest method that is used is linear interpolation in 3D. This simple method is illustrated using the following 2D example. If a simulated detector reading f_0 is desired at the coordinates (x_0, y_0) within a mesh cell that has bounding coordinates $\{x_1, x_2\}$ in the x-direction and $\{y_1, y_2\}$ in the y-direction, with known flux values $\{f_{1,1}, f_{1,2}, f_{2,1}, f_{2,2}\}$ at the 4 corners of the mesh cell, then f_0 would be calculated using the formulas:

$$t = \frac{(x_0 - x_1)}{(x_2 - x_1)} \cdot \quad u = \frac{(y_0 - y_1)}{(y_2 - y_1)} \tag{1}$$

$$f_0 = (1-t)(1-u)f_{1,1} + t(1-u)f_{1,2} + (1-t)uf_{2,1} + tuf_{2,2} \tag{2}$$

The next-most complicated method is quadratic polynomial interpolation in 3D. For this method, the flux values at a given number of the closest mesh-cell corners are required (at the closest 3 planes in the x-, y-, and z-directions). Quadratic polynomial interpolation in 3D has been the method of choice for simulating the detector readings in a CANDU reactor core model. A yet-more-complicated method that has been used for this purpose is 5-point cubic splines in 3D. These methods are all based on the assumption that the flux is smoothly-varying over all mesh cells. The detector readings in a full-core RFSP model are determined using the *INTREP module of RFSP (Rouben, 2002). The detector names and locations in the reactor core are defined within this module.

3. Description of the proposed method

The proposed method is based on flux reconstruction (Dahmani et al., 2010,Dahmani et al., 2011, Cho et al., 2000, Boer and Finnemann, 1985, Rempe et al., 1988, and Lee et al., 2002) involving the modulation of the intranodal diffusion flux and the form factor transport flux. The intranodal flux is an interpolation of the finite difference diffusion theory flux solution obtained over the entire reactor core. The form factor flux is based on a transport flux solution over one fuel lattice cell. The reconstructed flux obtained in this manner is a more realistic flux shape than could be obtained using the diffusion-based solution alone. The reconstructed flux allows a more accurate simulation of the detector flux that could theoretically be obtained at any point within the reactor core. In this study, the simulated detector flux obtained using this method is compared against real detector readings obtained from travelling flux detector (TFD) scans collected at a CANDU station.

The intranodal flux is interpolated over the *xy*-plane of a given mesh cell using a method that will presently be described, and is interpolated along the z-axis using standard quadratic polynomial interpolation. The *xy*-plane geometry of a typical mesh cell, including its dimensions, is illustrated in Fig. 1. In order to obtain the intranodal 9-parameter expansion in the *xy*-plane, 9 reference flux values are required. These are the node flux at the center of the mesh cell, the 4 edge fluxes at the centers of each cell edge face, and the 4 corner fluxes. The 4 edge fluxes are determined by interpolation of the node fluxes from the neighbouring mesh cells. The edge fluxes at the mesh boundaries are special cases that are determined using flux non-re-entrant boundary conditions. The 4 corner fluxes are determined by interpolation of the edge fluxes from the neighbouring mesh cells. The corner fluxes at the mesh boundaries are special cases that use fewer than 4 edge fluxes: the edge fluxes from in-core mesh cells only. Once these 9 fluxes have been determined for each mesh cell, a 9×9 matrix equation is solved to obtain the 9 expansion parameters for that mesh cell.

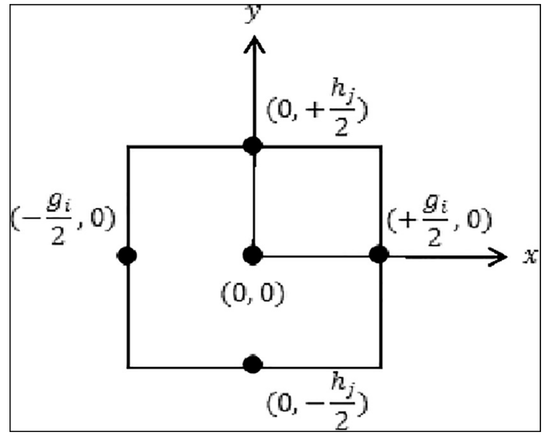

Fig. 1. Mesh Cell Coordinate System.

The 9 expansion parameters for the mesh cell appear in the flux quadratic expansion formula:

$$\phi(x,y) = a_1 + a_2x + a_3x^2 + a_4y + a_5yx + a_6yx^2 + a_7y^2 + a_8y^2x + a_9y^2x^2 \tag{3}$$

An expression for the node flux may be determined by integrating and averaging along both axes in the mesh cell in the xy-plane:

$$\phi_{ij} = \frac{1}{gh}\int_{\frac{-g}{2}}^{\frac{+g}{2}} dx \int_{\frac{-h}{2}}^{\frac{+h}{2}} dy\phi(x,y), \ \phi_{ij} = a_1 + \frac{1}{12}g^2a_3 + \frac{1}{12}h^2a_7 + \frac{1}{144}g^2h^2a_9 \tag{4}$$

Expressions for the edge fluxes may be determined by integrating and averaging along one axis in the mesh cell in the xy-plane while holding one coordinate fixed. For example, the expression for the W-edge flux is:

$$\phi_{ij}^W = \frac{1}{h}\int_{\frac{-h}{2}}^{\frac{+h}{2}} dy\phi\left(x = \frac{-g}{2}, y\right),$$

$$\phi_{ij}^W = a_1 - \frac{1}{2}ga_2 + \frac{1}{4}g^2a_3 + \frac{1}{12}h^2a_7 - \frac{1}{24}gh^2a_8 + \frac{1}{48}g^2h^2a_9 \tag{5}$$

Similar expressions are used for the 3 other edge-fluxes. Expressions for the corner fluxes may be determined by holding both coordinates in the mesh cell fixed. For example, the expression for the SW-corner flux is:

$$\phi_{ij}^{SW} = \phi\left(x = \frac{-g}{2}, y = \frac{-h}{2}\right), \ \phi_{ij}^{SW} = a_1 - \frac{1}{2}ga_2 + \frac{1}{4}g^2a_3 - \frac{1}{2}ha_4 + \frac{1}{4}gha_5 - \frac{1}{8}g^2ha_6 + \frac{1}{4}h^2a_7 - \frac{1}{8}gh^2a_8 + \frac{1}{16}g^2h^2a_9 \tag{6}$$

Similar expressions are used for the 3 other corner-fluxes. Once all 9 of the above equations have been formulated, and once all 9 left-hand-side fluxes are known, a matrix equation may be formulated (Dahmani et al., 2011):

$$\begin{bmatrix} \phi_{ij} \\ \phi_{ij}^W \\ \phi_{ij}^E \\ \phi_{ij}^S \\ \phi_{ij}^N \\ \phi_{ij}^{SW} \\ \phi_{ij}^{SE} \\ \phi_{ij}^{NW} \\ \phi_{ij}^{NE} \end{bmatrix} = [M] \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \\ a_9 \end{bmatrix} \tag{7}$$