VALIDATION OF HIGHER HARMONICS CALCULATION METHODOLOGY

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1. Introduction

In an operating reactor, neutron flux shape could get disturbed due to several reasons such asinsertion/removal of reactivity devices and localized perturbations due to reactivity feedbacks etc.The effect of such perturbations on power transients varies for different size of reactors. In large fastreactors, some of the designs exhibit significant spatial decoupling, particularly those designsincorporating an internal blanket. In such spatially decoupled cores, flux distributions are verysensitive to perturbations. As a quantitative indication of these decoupling characteristics, the *λ*modeeigenvalue separation has been frequently employed. The physical interpretation ofeigenvalue separation provides a measure of the spatial neutronic coupling among various parts of areactor and, hence, is indicative of the space-time dynamic behaviour [1].

To calculate higher mode eigenvalues and associated eigenvectors the methodology of flux higher eigen-modes calculation was implemented into DIF3D 10.0 code. This specific DIF3D modification is identified as DIFHH [2] where the decontamination (or in some literature known as deflation) method was adopted as the simplest solution[3].In order to validate and demonstrate the performance of DIFHH code modification, the simple benchmark problem based on paper prepared by Mr. Obaidurrahman [4] was chosen and investigated. The comparison of achieved trends and absolute values confirmed a favourable consistency between the reference and calculated results.

2. Theory

The main idea of the deflation method is todecontaminate system matrix from influence of exact eigenpair in the each iteration step. The iteration formula is written as follows:

$$x^{(m)} = A\frac{1}{k^{(m-1)}}\left\{x^{(m-1)} - \frac{u^T x^{(m-1)}}{u^T u}u\right\} \cong c_1 k_1^{(m)} u_1, \tag{1}$$

where **x** is an arbitrary vector defined as:

$$x = c_0 u_0 + c_1 u_1 + ... + c_n u_n, \tag{2}$$

and $\{u_0, u_1,..., u_n\}$is the set of *n* linearly independent eigenvectors. The appropriate eigenvaluescan be ordered in magnitude as [5]:

$$|k_0| \geq |k_1| \geq ... \geq |k_n| \tag{3}$$

For the evaluation of this analysis the eigenvalue separation (ε, EVS) numerical parameter was used. It is defined as the relative change of a given higher harmonic eigenvalue from the fundamental one. The first eigenvalue separation $\varepsilon_1$is defined as follows

$$\varepsilon_1 = (\lambda_1 - \lambda_0)10^5[pcm] \tag{4}$$

where$\lambda_1$is the first harmonic and λ_0 the fundamental eigenvalue ($1/k_{eff}$). To express the eigenvalue separation in units of pcm the results were multiplied by 10^5. To be consistent with the symbolism used in paper [4] both the EVS and ε symbols were used for eigenvalue separation.

3. Discussion and results

In paper [4] two effects of eigenvalue separation were studied; the core size effect and the core shape effect. Due to the availability of numerical and graphical results from paper [4] (hereinafter "the paper") a reactor with 1000 MW power and H/D ratio 1.2 was chosen for the first calculation case. For a permanently set power density and estimated thermal to electric efficiency (34.5%) we determined the following dimensions of the bare core: H = 376cm, D = 313cm. The schematic model of the bare reactor is presented in Fig. 1, where "H" is the core height, "D" is the core diameter, "A" indicates the orientation of the axial and "B" the radial section planes.

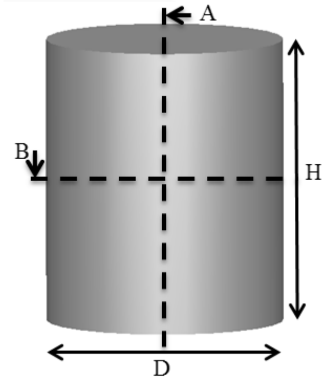


Fig.1:*Simple model of the benchmark core.*

The comparison of the first set of calculation results gave no meaningful results since the EVS1 (ε_1) and EVS2 (ε_2) values determined by DIFHH had been overestimated more than five times, compared to the results presented in the paper. The correctness of the geometry and material composition was confirmed by the author of the paper, but these discrepancies remained. The comparison of the shapes of the first and second harmonic neutron fluxes revealed some additional discrepancies. It turned out that in comparison with the [4] radial distribution of the second harmonic neutron flux (section plane B) had been rotated by approximately 10 degrees. To reveal the cause of these problems the sensitivity analysis of eigenvalue separation on core size was finally carried out for a constant core H/D ratio. The results of this analysis are presented in Fig.2.

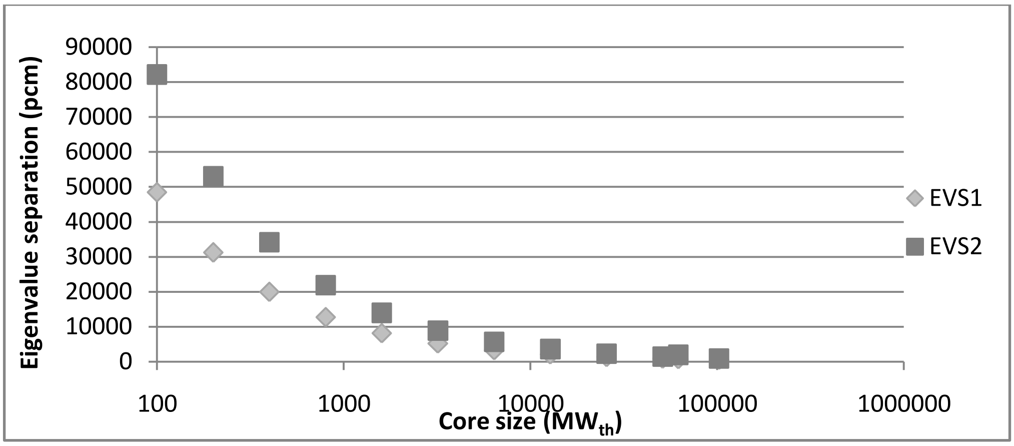
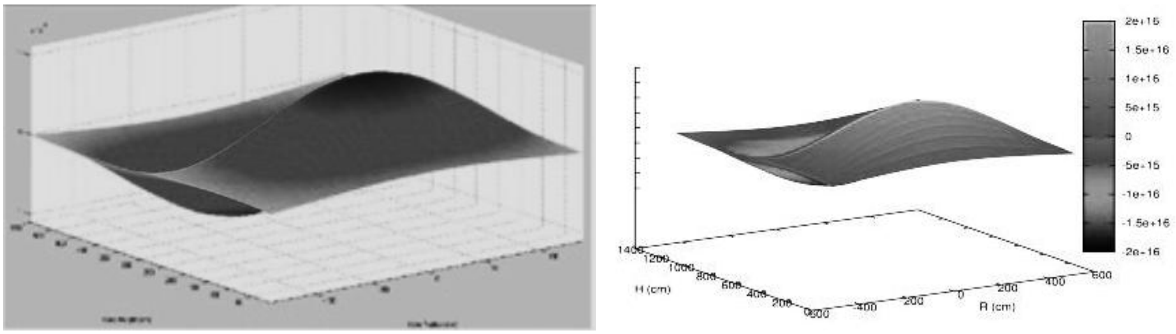


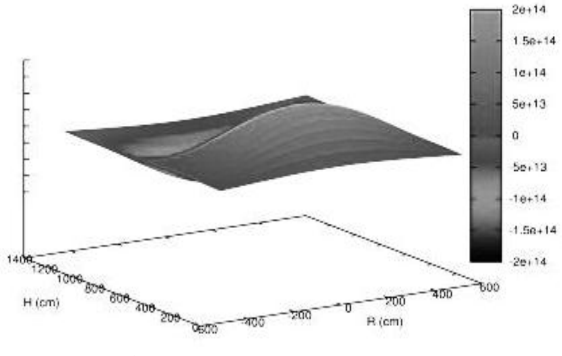
Fig. 2: *Effect of the core size on eigenvalue separation for H/D = 1.2.*

This analysis identified a power level of 51200 MWth, for which the results became consistent with the paper. The higher harmonic neutron fluxes also confirmed that the problem did not originate from DIFHH. Based on these assumptions, the relation of 1000MWe = 51200MWth was interpolated to all core parameters. The sources of the inconsistences and their impact will be further investigated but, they can be concluded as acceptable.The comparison of the axial distribution (section plane A) of the first harmonic neutron fluxes for H/D=1.2 is presented in Fig. 3. In Fig. 3-a the spatial distribution of fluxes for the reference 1000 MWe core is shown (screenshot from the paper). Our DIFHH results for the 1000 MWe and the equivalent 1000 MWe (51200MWth) cores are shown in Figure 3-b,c. The visual control has proven a relatively good consistency between the presented shapes, especially for the 1000 MWe and the equivalent 1000MWe DIFHH cases.



a) screenshot from the paper

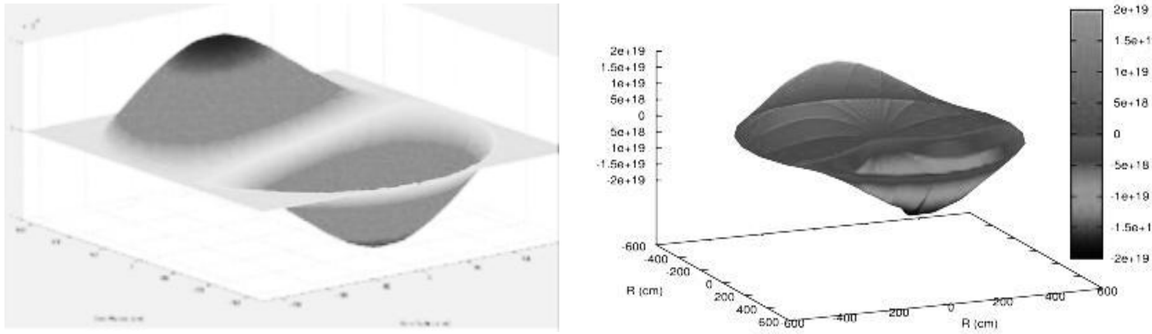
b)plots of DIF3DHH results



c)plots of DIF3DHH results

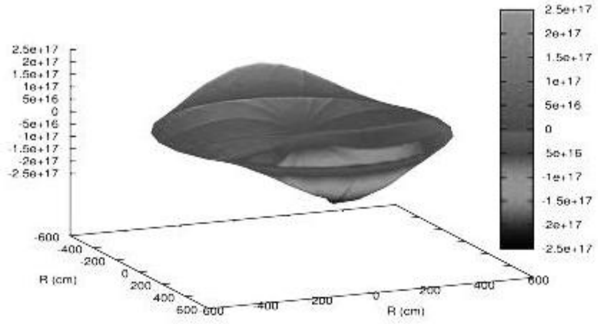
Fig. 3: *Comparison of the axial distribution of the first harmonic neutron fluxes for various core sizes.*

The same visual control was done for the radial distribution (section plane B) of the second harmonic neutron fluxes, which are presented in Fig. 4. As it was mentioned before, the symmetry of the distribution of the second harmonic fluxes calculated by DIFHH was shifted about 10 degrees in both cases (Fig. 4-b and Fig.4-c). Although the quality of Fig-a, where the reference shape is plotted, is not sufficient the rotation of the symmetry is still observable.



a)screenshot from the paper

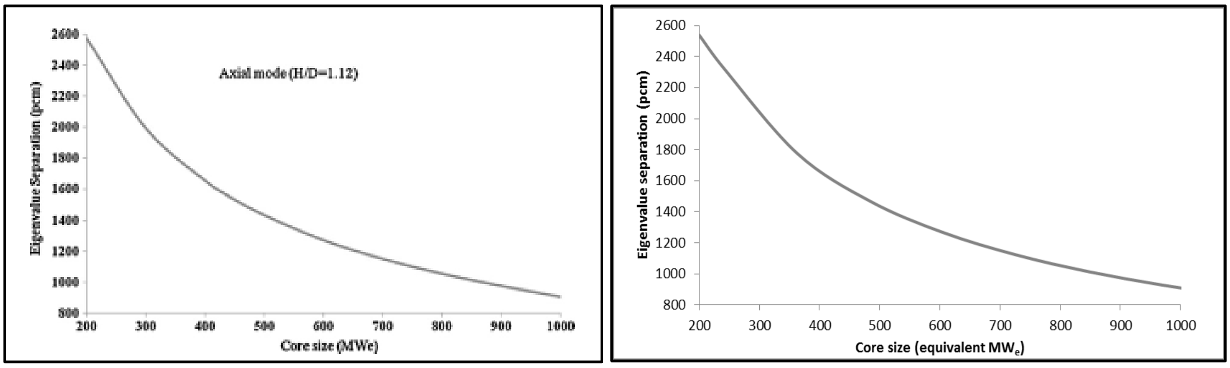
b) plots of DIFHH results



c) plots of DIFHH results

Fig. 4: *Comparison of the radial distribution of the second harmonic neutron fluxes for various core sizes.*

To understand the effect of core size the core H/D was kept constant in our calculations. The results of EVS1 vs. the core size are presented in Fig. 5, where the reference results are presented inFig. 5-a and the DIFHH results in Fig. 5-b. In both figures, the trends are similar, what can be considered as a positive correlation between codes independently developed for higher harmonic calculations. It should be noted, that the scale of core sizes was normalized based on the equivalent power conversion, which was previously determined to: 1000 MWe = 51200 MWth.



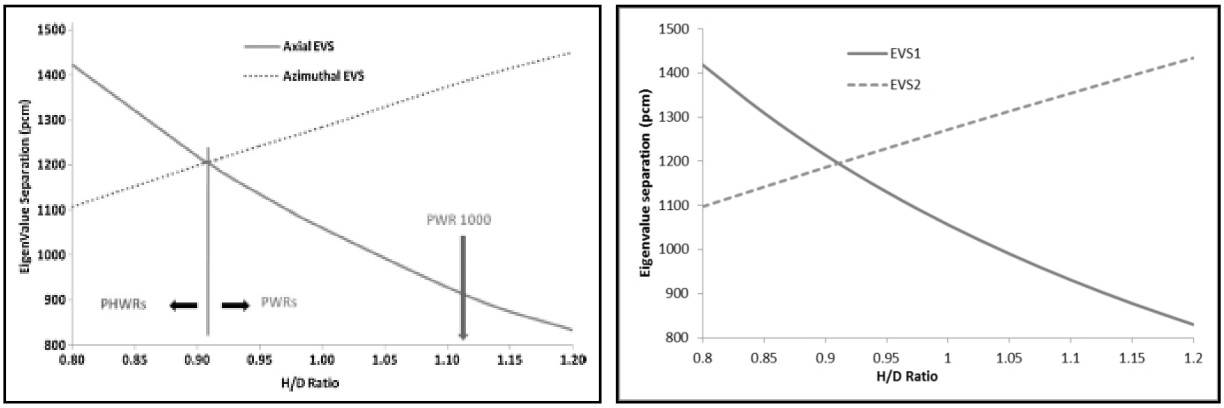
a) screenshot from the paper

b) DIFHH results

Fig. 5: *Influence of the core size on eigenvalue separation for H/D ratio 1.12.*

The second analysis deals with the investigation of the effect of core shape on eigenvalue separation. For the volume of the core which was equivalent to 1000 MW_e the first two eigenvalue separations were calculated as functions of core H/D ratios. The results of the eigenvalue separations are presented in

Figure 6. The reference results are presented in Figure 6-a and results calculated by the code DIF3DHH in Figure 6-b. In paper [3] the axial component was identified as the dominant one for the first harmonic neutron flux and the radial component for the second harmonic neutron flux. The visual comparison of the presented functions confirmed a favourable consistency between the reference and calculated results.



a) screenshot from the paper b) DIFHH results

Fig. 6: *Results of the effect of core shape on EVS for a core volume equivalent to 1000MW_e.*

4. Conclusion

In order to validate and demonstrate the performance of the DIF3DHH code modification, the simple benchmark problem based on paper prepared by Mr. Obaidurrahman was chosen and investigated. The comparison of achieved trends and absolute values confirmed favourable consistency between the reference and calculated results.Severe inconsistencies were identified for high H/D ratios during the analysis of the effect of core shape on EVS2. All discrepancies were successfully solved but extra effort was needed.Insufficient convergence criteria of the pointwise and average fission source vectorswas identified as the source of this discrepancy. The fundamental and the first eigenvalues were not influenced, but the cumulative relative error of these two eigenvalues, which propagates through the fission source vectors during deflation process, had significant impact on the second harmonic eigenvalue and neutron fluxes. The insufficient convergence may lead to incorrect evaluation of the investigated problem. This behavior can be explained by inadequate eigenvalue separation where the real solution is omitted and the system converges to an alternative solution.

5. Acknowledgement

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