Stability Analysis of a Liquid Metal Cooled Fast Reactor

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Abstract. Under specific transients, fast reactor cores show significant deviation in their power distribution which leads to spatial instability. As a quantitative indication of these decoupling characteristics, the λ-mode eigenvalue separation has been frequently employed. The physical interpretation of eigenvalue separation provides a measure of the spatial neutronic coupling among various parts of a reactor and, hence, is indicative of the space-time dynamic behaviour. In this paper the core-wide and regional stability of a Korean Prototype GEN-IV Sodium-cooled Fast Reactor (PGSFR) design is investigated by way of using deterministic approaches. To calculate higher mode eigenvalues and associated eigenvectors the methodology of flux higher eigen-modes calculation was implemented into the DIF3D 10.0 code, and is thoroughly described in the paper. This specific DIF3D modification is denoted as DIF3DHH where the decontamination (deflation) method was adopted as the simplest solution. In order to validate and demonstrate the performance of 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 a favourable consistency between the reference and calculated results. The D/H ratio of the reactor core was identified as an indicator of the extent of core stability, therefore the present analyses include the investigation of eigenvalue separation and flux distribution of various core D/H ratios. The findings and the results are discussed in the paper.

Key Words: higher neutron flux harmonics, reactor stability, deflation method, eigenvalue separation, PGSFR

1. Introduction

In an operating reactor, neutron flux shape could get disturbed due to several reasons, such as insertion/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 fast reactors, some of the designs exhibit significant spatial decoupling, particularly those designs incorporating an internal blanket. In such spatially decoupled cores, flux distributions are very sensitive to perturbations. As a quantitative indication of these decoupling characteristics, the eigenvalue separation has been frequently employed. The physical interpretation of eigenvalue separation provides a measure of spatial neutronic coupling among various parts of a reactor and, hence, is indicative of the space-time dynamic behaviour. To demonstrate the influence of eigenvalue separation on the core behaviour and stability, relation between flux tilt, transient terms attenuation constant and eigenvalue separation is given in a specific theoretical part of the paper. To calculate higher mode eigenvalues and associated eigenvectors in DIF3D [1], the decontamination method was implemented to the solver based on the finite difference method. The main idea of this method is to decontaminate system matrix from influence of exact eigenpair in each iteration step making use of the orthogonality relation between different higher harmonic vectors. This DIF3D 10.0 modification is hereinafter denoted as DIF3DHH [2]. The in-house graphical software BBK and DIFRES were used to plot neutron higher harmonic modes data stored in the RTFLUX and GEODST interference files. To validate the correct implementation of deflation method, study presented in [3] was repeated and available results were compared. Results of validation efforts are given in the special section of the paper and are judged as satisfactory. The specific part of the paper is devoted to the relation between different diameter to height ratios (D/Hs) of the Korean prototype of GEN-IV SFR (PGSFR) reactor core and the core egienvalue separation.

2. Theory

The theoretical part gives a short insight to the relation between basic core characteristics, reactor stability and eigenvalue separation.

2.1.Neutron Migration Length and Core Size

With the help of few basic fundamental diffusion equations and the simple slab geometry, the higher harmonics eigenvalue (λ_n) can be expressed as,

$$\frac{1}{\lambda_n} = \frac{k_\infty}{1+M^2B_n^2} \ , \tag{1}$$

where the geometric buckling is defined as $B_n = n\frac{\pi}{a},$ for a slab geometry of core extrapolated thickness a. The symbol k_∞ is infinite multiplication factor and M^2 is neutron migration area. Eigenvalue separation $\epsilon_1$between the first mode and fundamental mode is expressed as:

$$\epsilon_n = \lambda_n - \lambda_0; \ n = 1 \rightarrow \epsilon_1 = \lambda_1 - \lambda_0 \cong 3\left(\frac{M\pi}{a}\right)^2. \tag{2}$$

Thus, eigenvalue separation is inversely proportional to the square of the size of the reactor core. We can say that, if a reactor core is getting larger then eigenvalue separation is decreasing. On the contrary, if a neutron migration length is getting bigger, eigenvalue separation is increasing as well. Subsequently, due to the bigger neutron migration length, we expect bigger eigenvalue separation in fast reactor cores.

2.2.Higher Harmonics Amplitude Perturbations

For studying the dynamics of harmonics modes, we use the time-synthesis modal expansion technique [4], which is often used for solving space-time reactor problems. The idea is to choose a set of ψ functions from which any instantaneous flux distribution $\boldsymbol{\phi}$ that occurs during the transient may be constructed by a linear combination. Using this approach, the modal expansion for the space and time-dependent neutron flux and precursor concentration $\boldsymbol{C}(t)$ have following forms [5]:

$$\boldsymbol{\phi}(t) = N_0\boldsymbol{\psi_0} + \sum_{m=0}^{M}\boldsymbol{\psi_m}n_m(t) \ , \tag{3}$$

and

$$\boldsymbol{C}(t) = C_0\,\boldsymbol{\psi_0}/\boldsymbol{v} + \sum_{m=0}^{M}c_m(t)\,\boldsymbol{\psi_m}/\boldsymbol{v} \ , \tag{4}$$

where N_0 and C_0 are magnitudes in steady state, n_m and c_m are time-dependent expansion coefficients. As the spatial expansion modes $\boldsymbol{\psi_m}(\boldsymbol{r})$, the Inhour modes [6] should be employed. The fundamental mode of delayed neutrons is almost the same as the static eigenfunction found in a k_{eff} search. However, under certain conditions, the prompt neutron fundamental flux shape is not the same as the static eigenfunction. When this condition exists, “kinetic distortion” is present. By neglecting kinetic distortion, which is a good assumption for the lower order-harmonics, we can make an approximate calculation, that the Inhour-mode eigenfunction for a given harmonics is the same as the λ(static)-mode eigenfunction [5]. Therefore, the neutron flux higher modes $\boldsymbol{\psi_m}$ (eigenvectors) of core-statics eigenvalue problem are chosen in our approach. If the system is critical before the transient, applying the first-order perturbation formula for reactivity, and by using the Laplace transformation, the higher-harmonics amplitudes can be simplified and become:

$$\hat{n}_n = N_0 \frac{\hat{\rho}_{n,0} - \sum_{l=1}^{6} \frac{s\hat{\rho}_{n,0}^{d_l}}{s+\lambda_l}}{s\Lambda_n + \epsilon_n + \sum_{l=1}^{6} \frac{s\beta_l}{s+\lambda_l}} \ , \tag{5}$$

where Λ_n is the neutron generation time for n-th mode, $\rho_{n,0}$ stands for the modal reactivity (here interpreted as the excitation reactivity of the n-th mode, which is introduced by a net change in the 0-th mode reaction rate) and $\rho_{n,0}^{d_l}$ represents the l-th group delayed neutron reactivity contribution. It can be seen that impact of mode eigenvalue separation on transient terms amplitudes is notable. From the reactor stability point of view, the influence of neutron flux higher harmonics modes to the transient behaviour of core can be mitigated by their higher eigenvalue separation.

2.3.Static Neutron Flux Tilt

The theoretical relation between flux tilt and eigenvalue separation was first presented by Rydin [7]. His work was expanded by cooperation with Beckner [8]. They evaluated the eigenvalue separation of the coupled-core loadings in the solid homogeneous assembly using flux tilt method. Next, Hasmito [5] presented a practical formula, which had both simplicity and generality for extracting the eigenvalue separation from flux tilt measurements. The derivation is based on modified explicit high order perturbation method with application of perturbation formulation to the first-order:

$$tilt = \frac{\rho_{0,p} C_{p1}}{\epsilon_1} \cong \frac{\langle \boldsymbol{M\phi'} \rangle_L - \langle \boldsymbol{M\phi'} \rangle_R}{\langle \boldsymbol{M\phi'} \rangle} \ , \tag{6}$$

where $\rho_{0,p}$ is the reactivity of initial asymmetric perturbation, C_{p1} stands for correction factor maintaining criticality, $\boldsymbol{M}$ is production operator and $\boldsymbol{\phi'}$ represents perturbed flux. Moreover $\langle \ \rangle_L, \langle \ \rangle_R$ are integrals over the left and right half core volume and volume. From Eq. (6) it can be said, that a large sized reactor core will exhibit more flux tilt for the same magnitude of asymmetric reactivity perturbation and accordingly a reactor with big neutron migration length will exhibit less flux tilt for the same perturbation.

2.4.Power Method with Deflation

The principle of the deflation method implemented to finite difference solver in DIF3D 10.0 is to decontaminate system matrix from influence of exact eigenpair in each iteration step. In principle, the iteration formula is written as follows:

$$\boldsymbol{x^{(m)}} = \boldsymbol{A} \frac{\boldsymbol{1}}{\boldsymbol{k^{(m-1)}}} \left\{ \boldsymbol{x^{(m-1)}} - \frac{\boldsymbol{u^T x^{(m-1)}}}{\boldsymbol{u^T u}} \boldsymbol{u} \right\} \cong c_1 {k_1}^{(m)} \boldsymbol{u_1} \ , \tag{7}$$

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

$$\boldsymbol{x} = c_0 \boldsymbol{u_0} + c_1 \boldsymbol{u_1} + \cdots + c_n \boldsymbol{u_n} \ , \tag{8}$$

and $\{\boldsymbol{u_0}, \boldsymbol{u_1} \dots, \boldsymbol{u_n}\}$ is the set of n linearly independent eigenvectors. The appropriate eigenvalues can be ordered in magnitude as:

$$|k_0| > |k_1| \geq \cdots \geq |k_n|. \tag{9}$$

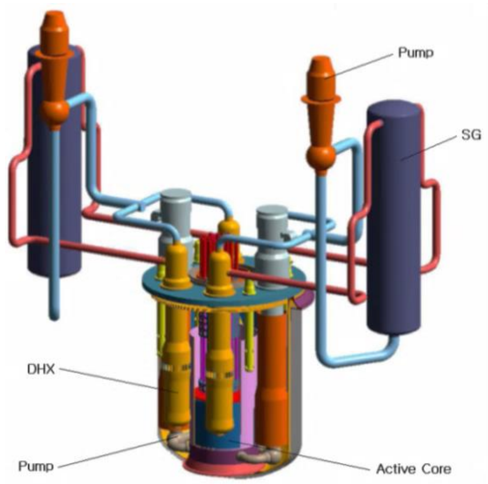
For the validation purposes the first eigenvalue was always also calculated by Eq.10:

$$k_1 = \frac{k_0^{(m)} - k_0^{(m-1)}}{k_0^{(m-1)} - k_0^{(m-2)}} k_0 \ . \tag{10}$$

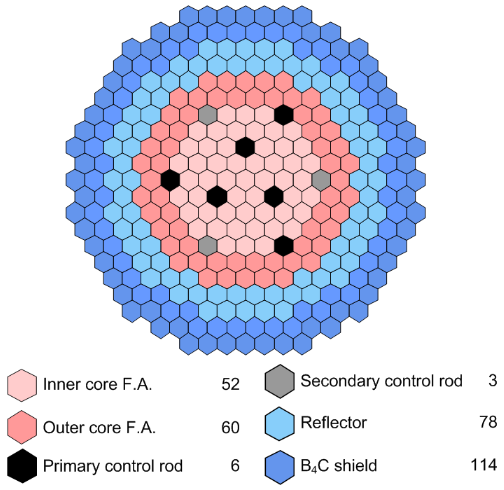
This iterative equation is valid only for the Power method without applied acceleration.

3. Overview of the PGSFR Core Design

As a target core the Korean PGSFR core [9] was used in our calculation. The objectives of PGSFR are to test and demonstrate the performance of transuranics containing metal fuel required for commercial SFR and to demonstrate the transmutation capability of a burner reactor as a part of an advanced fuel cycle system. PGSFR is a pool type reactor with electric capacity of 150 MWe (392 MWt) and features a proliferation-resistant metallic core without blanket. The fuel region is divided to two angular rings of inner and outer fuel assemblies as it is shown in *FIG. 1*. The metallic fuel of U-Zr (or U-TRU-Zr) is used as the driver fuel with an average enrichment less than 18.5 % ^{235}U. Due to radiation damage limitation, the fast neutron fluence should not exceed $4.0 \cdot 10^{23}$ n/cm^2. The active core height is 97.7 cm and a radial equivalent radius reaches 1.58 m. There are 217 fuel pins in each fuel assembly (F.A). The reactivity control and shutdown system consists of 9 primary and secondary control rods, which are used for power control, burnup reactivity compensation and reactor shutdown. In the current design HT9M steel is used as a cladding material. The designed input core temperature is 390 °C and the output temperature reaches 545 °C.



a)



b)

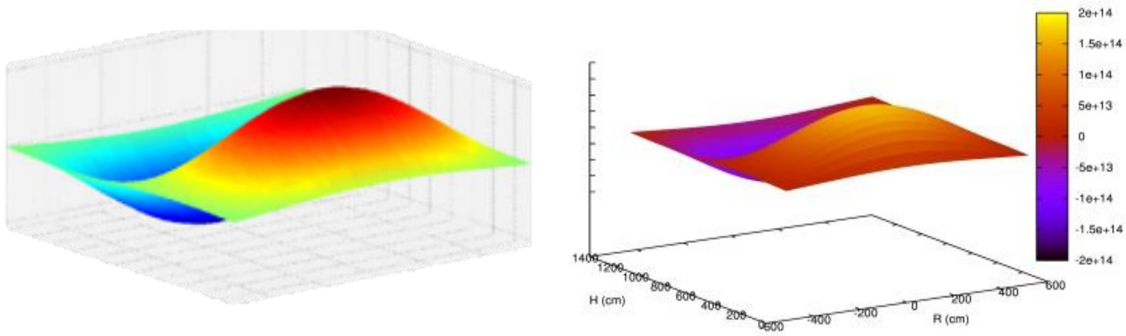
FIG. 1. The sketch and active core fuel loading pattern of PGSFR [9].

According to the latest information, a prototype SFR shall be available by 2017, the specific design shall be approved in 2020 and the construction of a prototype SFR shall be started in 2028. The PGSFR has now entered the preliminary design phase.

4. Validation

The performance of DIF3DHH code was tested by the simple benchmark problem specified in the paper of Mr. Obaidurrhman. In paper [3] two effects of eigenvalue separation were studied; the core size effect and the core shape effect. In our case just core shape effect study was carried out. Due to the availability of numerical and graphical results from paper

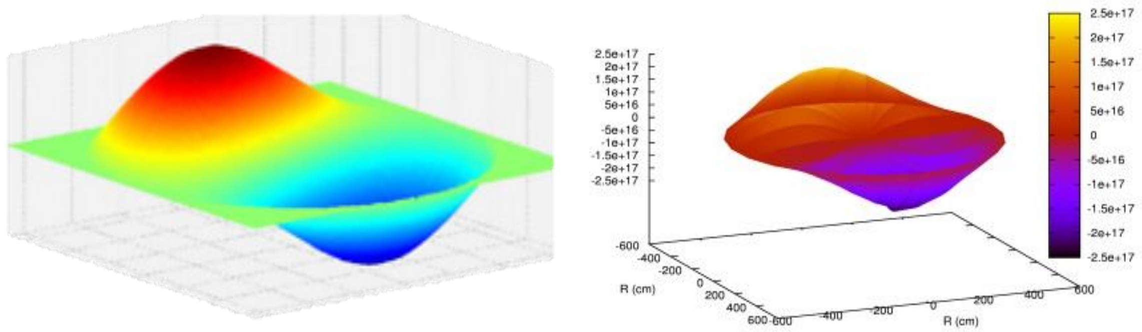
[3] (hereinafter “the paper”) a reactor with 1000 MW power and H/D ratio 1.2 was chosen for the first calculation case. The dimensions and material composition of the investigated core were based on the V1000CT-1 VVER-1000 coolant transient benchmark analysis. Used cross section (XS) data were based on 620 group MATXS library prepared by using NJOY99 and ENDF/B-VII.0 evaluated data. The obtained region-wise neutron fluxes were used for homogenisation and group condensation in the TRANSX code. The final calculations were performed by the DIF3DHH code on one-group problems and R-THETA-Z geometry. The comparison of the axial distribution of the first harmonic neutron fluxes for H/D=1.2 is presented in *FIG. 2*. In *FIG. 2-a* the spatial distribution of fluxes for the reference 1000 MWe core is shown (screenshot from the paper). Our DIF3DHH results are shown in *FIG. 2-b*. The visual control has proved a relatively good consistency between the presented shapes.



a) screenshot from the paper [1] b) BBK plots/DIF3DHH

FIG. 2. Comparison of the axial distribution of the first harmonic neutron fluxes.

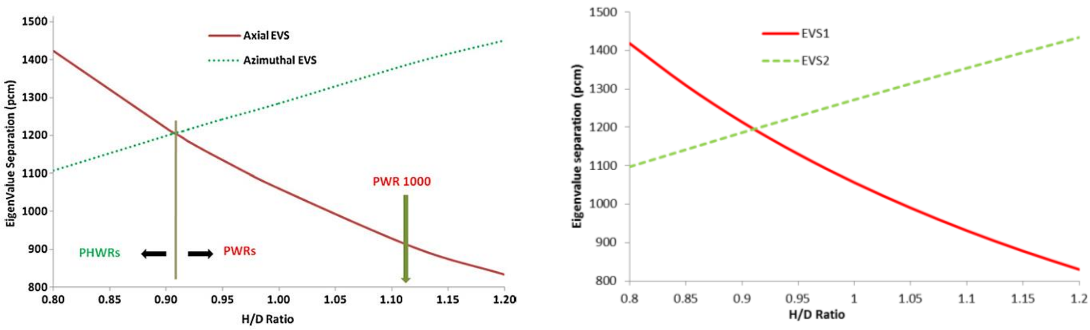
The same visual control was done for the radial distribution of the second harmonic neutron fluxes, which is presented in *FIG 3*. The symmetry line of the second harmonic flux distribution calculated by DIF3DHH is shifted approximately by 10 degrees.



a) screenshot from the paper [1] c) BBK plots/DIF3DHH

FIG. 3. Comparison of the radial distribution of the second harmonic neutron fluxes.

The next analysis deals with the investigation of the effect of core shape to eigenvalue separation. The first two eigenvalue separations (EVS1 and EVS2) were calculated for the different H/D core ratios. Again, the reference results are shown on the left and DIF3DHH results on the right side of *FIG. 4*. 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. In both figures, the trends are similar, what can be considered as a positive correlation between codes independently developed for higher harmonic calculations.



a) screenshot from the paper [1] c) DIF3DHH results

FIG. 4. Results of the effect of core shape.

The visual comparison of the presented functions confirmed a favourable consistency between the reference paper and own calculated results.

5. Higher Harmonics calculation of PGSFR core

Before starting a comprehensive analysis of the higher neutron fluxes it is beneficial to compare the calculated results of harmonic eigenvalues with other liquid metal fast breeder reactor designs (LMFBR) [10]. For the calculations, the KAFAX-E70 [11] neutron XS library was used. The comparison of the fundamental and the first four harmonic eigenvalues is presented in Table I below.

TABLE I: COMPARISON OF EIGENVALUES OF VARIOUS LMFBR REACTORS [10].

Eigenvalue	PGSFR	*LMFBR1	**LMFBR2	Eigenvalue	PGSFR	**LMFBR1	**LMFBR2
k_0	0.9976	1.0000	1.0000	k_2	0.8074	0.3415	0.7111
k_1	0.8091	0.6225	0.8774	k_3	0.6911	0.2039	0.5342

* 250MWe, ** 1200MWe

As it is shown in the theoretical part, small compact reactor cores tend to have larger eigenvalue separations than big ones. Based on this statement, one could assume that the higher harmonic eigenvalues of the PGSFR core would be even smaller than the ones for the LMFBR 250 MWe reactor. However, due to the different fuel types, neutron spectra, core arrangement, D/H ratios and thus different migration lengths of the abovementioned LMFBR reactors and PGSFR, our calculated values seem to be reliable.

2.5. Spatial Distribution of the Neutron Fluxes

In the next step, the PGSFR spatial higher flux harmonics were calculated and plotted by BBK software. Relevant radial and axial distributions are shown in following *FIG.5*.

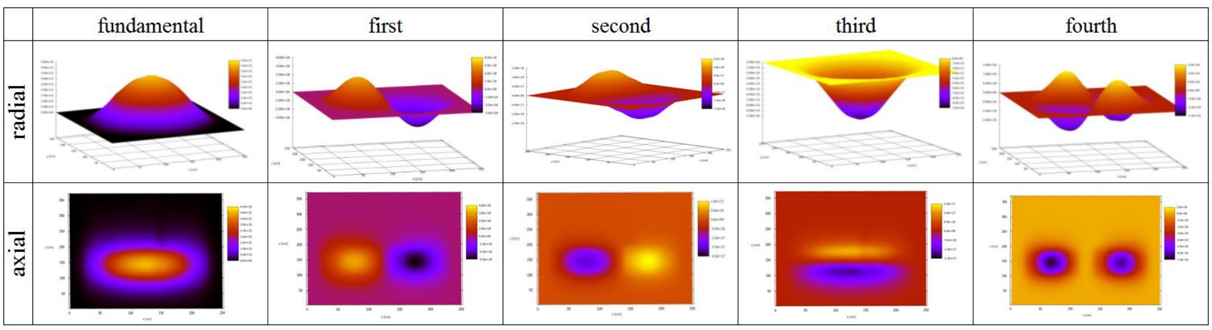


FIG. 5. Spatial distributions of PGSFR neutron fluxes.

The spatial distribution of the fundamental neutron flux is almost circularly symmetric. The ideal symmetry is just disturbed due to the control rods position. There is also a strong decrease of neutron flux towards the core periphery where the B_4C shielding material is located. In terms of the first harmonic neutron flux there is one positive and one negative peak of its radial distribution. The flux zones are symmetrical to the radial neutral line. In the axial direction the cosine shape of the fundamental neutron flux is split into a positive and negative part. The radial distributions of the first and second harmonic neutron fluxes are very similar, just the flux zones are mutually rotated by approximately 90 degrees. The radial and axial distributions of the third harmonic neutron fluxes differ from the previous 2 harmonics. While for the first two harmonic neutron fluxes the radial component was the dominant one, for the third harmonic neutron flux the axial component has become the dominant. In the axial direction, there is a positive and a negative peak of the neutron flux. These zones are symmetrical to the axial neutral line, which is perpendicular to the z axis. Similarly to the first and second harmonic neutron fluxes, the radial component of the fourth harmonic neutron flux is the dominant one. Unlike the first two harmonic fluxes, there are two positive and two negative peaks of the fourth harmonic neutron flux. The positive flux zones lie opposite to each other and the negative zones are rotated by approximately 90 degrees compared to the positive ones. The absolute values of negative neutron fluxes exceed the values of positive fluxes.

2.6. Core shape modification strategies

Following the methodology presented in validation part, the effect of core shape was also investigated for the PGSFR core model. The D/H ratio of the original PRSFR core is approximately 1.78, therefore range of investigated D/H ratios was carefully selected to lie in the range of D/H ± 0.5 of the original core. Since the investigated reactor core is composed of hexagonal assemblies, the D/H ratio in our analysis represents the ratio of the cylindrical core equivalent diameter and the fuel column effective height. Subsequently for the given D/H ratio and preserving the volume of the core, new effective diameter and effective height are determined. Once these parameters are known, the cylindrical core can be transformed back to hexagonal geometry and the fuel assembly pitch can be calculated preserving the total number of fuel assemblies.

The D/H ratio is the ratio of the diameter and height of the core; however the whole reactor core consists of other parts (reflectors, shielding, control rods etc.) which were not taken into account in procedure described before. To assess the impact of these elements on eigenvalue separations two calculation approaches were investigated, denoted by the BASIC and RMOD tags. In the BASIC approach the height of axial nonfuel elements was kept the same as in original PGSFR design. In radial direction the number of shielding and reflector assemblies was kept constant, and due to the new uniform assembly pitch, the volumes of these assemblies were modified. Since such modifications change the mass ratios of core elements; the physical behaviour of the core may also be altered. In the RMOD approach the thicknesses of the axial reactor core segments were adjusted to keep the fuel to reflector height ratios same as in the original design. The equivalence of the fuel to radial core element mass ratios was achieved by the change of reflector element density. The total number of radial reflector assemblies was preserved.

2.7.Results of core shape modifications

The results of the first four eigenvalue separations obtained by the BASIC and RMOD approaches are shown in *FIG. 6.*

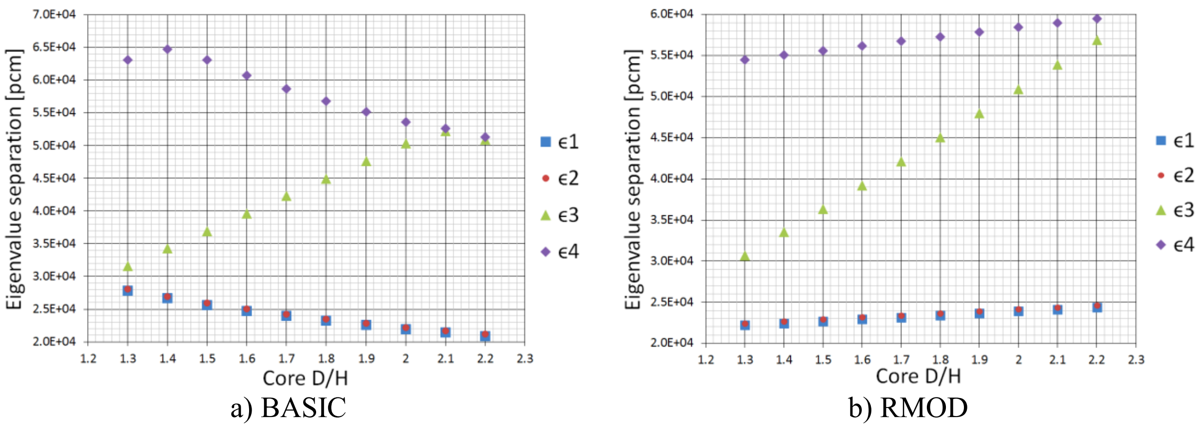


FIG. 6. Results of eigenvalue separations of the BASIC and RMOD approach.

As it can be seen, the first two harmonic eigenvalues calculated by the BASIC approach show decreasing tendencies. The total decrease of ϵ_1 and ϵ_2 is 6914 and 6925 pcm respectively. The average difference between the ϵ_1 and ϵ_2 values is 260 pcm. A strong 19200 pcm increase of the third eigenvalue separation, which is mainly driven by axial component, can be seen for D/H 1.3 – 2.1, but for D/H 2.2 the ϵ_3 value drops by 6467 pcm. The absolute values of ϵ_4 are twice as high as ϵ_1 and ϵ_2, but there is a downward tendency with a break point at D/H 1.4. The total decrease of ϵ_4 is 11749 pcm. By adjusting the radial reflector, to keep the mass ratios of the original core, the neutron spectrum is not expected to be significantly altered due to the reflector moderation effects. Based on these assumptions we can predict steeper increase of eigenvalue separation, and thus more stable behaviour of the RMOD cores compared to the BASIC cores. As it can be seen from the *FIG. 6-b*, the first two eigenvalue separation curves show increasing trends, thus the core seems to be more stable for higher D/H ratios. The values of the first two eigenvalue separations are very close to each other; their average deviation is only 258 pcm. The total increase of the ϵ_1 and ϵ_2 parameters between D/H 1.3 and 1.8 is 2172 and 2202 pcm. From the results we can see a large 26000 pcm linear increase of the ϵ_3 parameter between D/H ratios 1.3 and 2.2. The fourth eigenvalue separation is also increasing between small and large D/H ratios. The total increase of ϵ_4 is 5027 pcm.

An interesting finding is the increase of first eigenvalue separation between D/H 1.3 and 2.2 in RMOD case, and on the other hand sharp decrease of the same parameter in BASIC modelling approach. This phenomenon occurs due to the change of volume ratios of fuel and reflector elements for different D/H ratio. The BASIC modelling approach increases mass of the reflector material with the higher D/H ratios, affects the leakage term, and thus shortens the migration length of neutrons in the core affecting mainly radial flux distributions. Hence the decrease of eigenvalue separation was not driven only by the change of D/H ratio but also by spectrum shifting due to increased mass fraction of reflector elements.

2.8.Comparison of the higher harmonic modes

As it was shown in *FIG.6-a*, the curves of eigenvalue separation were not smooth for each harmonic component. There were several sudden drops and increases of the eigenvalue separation parameter. To reveal the cause of this behaviour, the radial harmonic functions are compared for various D/H ratios. The results of the first four harmonics of the BASIC cores are shown in Table II ÷ Table IV. As can be seen in Table II, neither the first nor the second harmonic function shows significant changes of its radial distribution between D/H 1.3 and 2.2. One positive and one negative peak of the flux appear on the figures. It can be concluded that the increase of the core D/H ratio does not significantly influence the spatial distribution of the first and second harmonic neutron fluxes, but due to eigenvalue changes the core becomes less stable. Following results were postprocessed by the DIFRES code.

TABLE II: RADIAL DISTRIBUTIONS OF THE FIRST AND SECOND HARMONIC FLUXES.

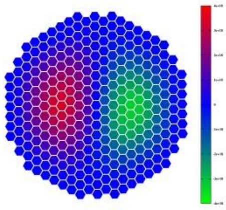
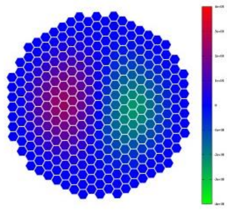
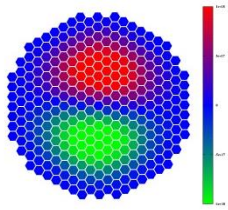
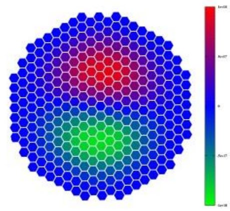
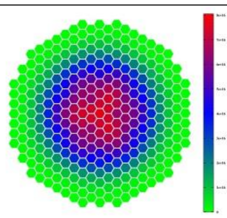
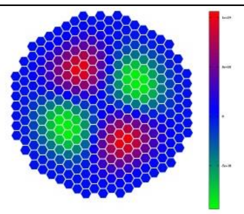
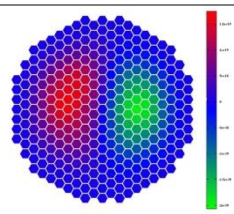
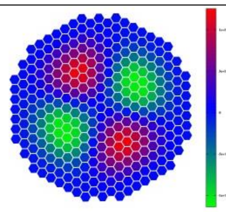
The first harmonic function		The second harmonic function	
 D/H 1.3	 D/H 2.2	 D/H 1.3	 D/H 2.2

Table III shows the reason of eigenvalue separation break points noticed in the BASIC modelling approach. In case of the third harmonic, the axial component is dominant for the D/H ratios ranging from 1.3 to 2.0, but for D/H ratios higher than 2.0 the radial component became the dominant one. Instead of one peak located at the core centre there are two positive and two negative peaks of the harmonic neutron flux.

TABLE III: RADIAL DISTRIBUTIONS OF THE THIRD AND FOURTH HARMONIC FLUXES.

The third harmonic function		The fourth harmonic function	
 D/H 2.0	 D/H 2.1	 D/H 1.4	 D/H 1.5

For D/H bellow 1.4 the radial distribution of the fourth harmonic neutron flux is similar to the first harmonic neutron flux. The core neutral line is almost perpendicular to the *x* axis, but a slight clockwise rotation can be observed. For D/H ratios above 1.5 there are two positive and two negative peaks of the neutron flux.

6. Conclusion

This paper presents a brief overview of the original basic research performed in the framework of GEN IV reactor development. In the theoretical part we demonstrated the high impact of mode eigenvalue separation on higher-harmonics amplitudes. Consequently, from the reactor stability point of view, the influence of neutron flux higher harmonics modes on the transient behaviour of core can be decreased by their higher eigenvalue separation. In addition, it is shown that a reactor with higher eigenvalue separation will exhibit less flux tilt for the asymmetric reactivity perturbation. The new DIF3DHH code modification was partially validated by the simple benchmark published by Mr. Obaidurrahman. The comparison of achieved trends and absolute values confirmed favourable consistency between the reference and calculated results. It was found, that the insufficient convergence criteria may lead to incorrect evaluation of the investigated problem. The first four PGSFR spatial higher flux harmonics were successfully calculated. While the first two harmonic neutron fluxes were mainly driven by radial component, for the third harmonic neutron flux the axial component became dominant. The PGSFR eigenvalues were compared to published results of other LMFBR systems, where our results can be judged as satisfactory. Two modelling approaches were used to assess the effect of core shape for the PGSFR core. In general, it can be concluded that in terms of the stability of the PGSFR reactor the mass ratio of fuel and nonfuel core internals and the thickness of reflector elements are more important than the D/H ratio of the core itself. In order to precisely investigate the influence of core D/H ratio on the higher harmonic components of eigenvalues and neutron fluxes, and to avoid shape changes of higher harmonic flux zones of the core, it is advantageous to keep constant fuel-reflector mass ratios for the investigated D/H ratios of the core. It can be concluded, that for the RMOD modelling approach, eigenvalue separations for all investigated harmonics achieve higher values for larger D/H ratios. Although the analysis was performed for the Korean SFR reactor concept, the achieved results could contribute to the development of the majority of innovative fast reactors. The achieved results will be useful in safety analyses of transient processes and studies on core optimization.

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