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► **To cite this version:**

C. Patricot, O. Fandeur, Am. Baudron, D. Broc. Neutronic calculation of deformed cores development of a time-dependent diffusion solver in CAST3M. PHYSOR 2016 – Unifying Theory and Experiments in the 21st Century, May 2016, Sun Valley, United States. pp.on CD - ROM. hal-02416302

HAL Id: hal-02416302

<https://hal.science/hal-02416302>

Submitted on 17 Dec 2019

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EXTENDED SUMMARY:

NEUTRONIC CALCULATION OF DEFORMED CORES: DEVELOPMENT OF A TIME-DEPENDENT DIFFUSION SOLVER IN CAST3M, A MECHANICS DEDICATED FINITE ELEMENTS CODE

Cyril Patricot, Olivier Fandeur, Anne-Marie Baudron, Daniel Broc

1. INTRODUCTION

Nuclear reactor cores can be deformed by thermic dilatations, irradiation effects or during some particular accidental transients. These deformations are likely to impact neutronics. Fast neutron reactors, because of their neutronic (mostly the high role of leakages in the neutron balance and the weak fraction of delayed neutrons) and thermic (high temperature gradients and strong potential temperature variations during accidents) features are particularly sensible to these mechanical effects. As a consequence, in the frame of the fourth generation reactor development, the need for tools able to assess the neutronic behavior of deformed cores is growing. In the same time, the computer power increase makes possible new calculation methodologies.

First of all, it is essential to remind that Monte-Carlo codes are, of course, intrinsically able to take into account any kind of deformations. However the CPU-time cost of these Monte-Carlo simulations and the difficulty to make kinetic or adjoint calculations lead to the research of equivalent flexibility with determinist codes.

Usually direct calculations are performed to deduce global feedback coefficients from studies of simple uniform dilatations. This approach lacks of accuracy and is unusable for complex core distortions. We can identify no less than three alternatives in the literature. The first one, which is a wide family of methodologies, consists in using the first order perturbation theory. It was used, for example, to study the Fast Flux Test Facility (FFTF) [1-2]. More recent developments on this field aim at defining local feedback distortion coefficients to be used in transient calculations [3-4]. The second alternative is a consequence of a constraint in most current deterministic neutronic codes: the mesh must be regular (this hypothesis allows substantial speeds up). Mesh projection methods are therefore required to describe deformed cores [5]. The size of the calculation mesh can be reduced for a better accuracy and one gets like this the pixelisation method [6] which works fine with fast neutron spectrum. The last alternative is based on spatial mesh deformation for a better description of the geometry distortion. In [7] it is shown that this kind of methods is more precise than mesh projection for a control rod movement in VVER-type reactors. However, as we said before, most deterministic codes do not allow mesh distortion. In order to follow this way, it is therefore often necessary either to rewrite a neutronic solver in an adequate environment ([8] is a perfect example) or to adapt a neutronic solver to allow non-regular meshing.

In this paper, we follow the mesh deformation approach. For the sake of simplicity, the approach was fully developed using the same code. As a consequence, we present a diffusion solver developed in CAST3M [9], a finite element code, developed at CEA and dedicated to structural mechanics. CAST3M facilitates the mesh manipulations and the coupling between mechanics and neutronics. In addition to verification tests versus APOLLO3[®] [10], the CEA reference deterministic code,

on non-deformed cases, our solver was confronted to the pixelisation approach presented in [6] and to the TRIPOLI-4 code [11], a neutronic Monte-Carlo code developed at CEA, on flowering deformations of the core of PHENIX, a Sodium Fast Reactor (SFR). Finally, recommendations are made in order to correctly describe radial deformations of cores with this approach.

2. SOLVER PRESENTATION

2.1. Steady-State Solver

The solver relies on CAST3M ability to numerically solve the Poisson's equation. We solve the multi-group diffusion equation with classical power iterations. Thanks to CAST3M architecture, this solver is very flexible and can use several kinds of finite elements, on different meshes, in 1, 2 or 3D modeling, with, among others, Dirichlet and/or Neumann boundary conditions.

This solver was confronted to the Minos [12] solver of APOLLO3[®] (used in diffusion) on PHENIX, with beginning-of-life compositions, in 3D. Both codes use here the same 33-groups macroscopic cross-sections issued from ECCO (ERANOS [13] module) cell calculations. Effective multiplication factors computed are 1.01498 for Minos (APOLLO3[®]), and 1.01349 for CAST3M (-145pcm).

2.2. Kinetic Solver

We use an implicit time integration scheme for the kinetic diffusion equation, coupled with delayed neutrons. The problem is solved with an iterative technique similar to the one used for steady-state calculations. An acceleration technique, implemented in CRONOS2 [14] and Minos, based on residual minimization of a condensed equation, is also used.

This kinetic solver was confronted to the Minos solver of APOLLO3[®], on PHENIX core configuration in 2D. The same time integration scheme is used by both codes. After initialization (a calculated steady-state), we consider a simple transient with instantaneous control rods insertion at $t = 1s$ and instantaneous control rods withdrawal at $t = 5s$.

The power evolution during this simple transient, calculated with large time steps of 1s, is given in figure 1, on the left. On the right part of figure 1, one can see a recalculation of the power decrease between $t = 1s$ and $t = 2s$ with smaller time steps. This last calculation allows checking that the prompt neutron inertial term is correctly treated by our solver.

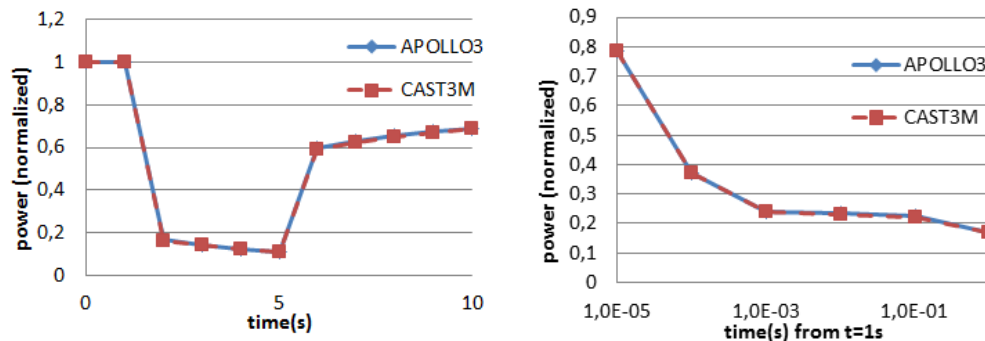


Figure 1. Power evolutions versus time, calculated with APOLLO3[®] and CAST3M, on a simple academic transient on PHENIX in 2D. On the left, time steps of 1s are used. On the right, this is a recalculation of the power decrease from $t = 1s$ to $2s$, with smaller time steps.

We can conclude from these comparisons that the solver was correctly developed.

3. APPLICATION TO FLOWERING OF PHENIX

3.1. Mesh and Geometry Distortion Treatment

Only 3D calculations are presented in the following. Sub-assemblies are homogenized (including inter-wrapper sodium) and cut in three diamonds.

When the core is (radially) deformed, the central nodes follow their sub-assemblies, while nodes between sub-assemblies are moved to the barycenter of the new positions of the adjacent sub-assemblies centers. This way of deforming meshes does not maintain volumes. We have therefore to adapt the macroscopic cross-sections and the concentration of each delayed neutron precursor.

3.2. Validation in Steady-State

We used the TRIPOLI-4 Monte-Carlo code, to validate the ability of our solver to calculate reactivity effects of radial core deformations. The considered deformation is a central flowering of PHENIX's core. Mechanical calculations are done with CAST3M.

The comparison between TRIPOLI-4, our neutronic solver developed in CAST3M and the pixelisation technique developed with APOLLO3[®] [6] is given in figure 2.

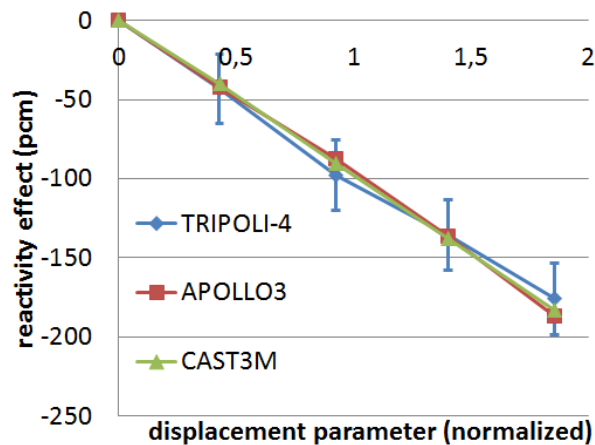


Figure 2. Comparison of reactivity effects calculated on a radial core deformation by TRIPOLI-4, APOLLO3[®] with pixelisation technique and CAST3M with deformed mesh.

One can see the good consistency between the results of these three codes.

3.3. Comparison with the Pixelisation Technique Developed with APOLLO3[®] in Kinetic

Unfortunately we do not have the possibility to validate our new methodology in kinetic with TRIPOLI-4. We compared instead our new solver with the pixelisation technique developed with APOLLO3[®].

We consider here the following transient:

- A slow central flowering of PHENIX core during one second,
- No additional distortion during half a second,
- Instantaneous removal of the device pushing on sub-assemblies at $t = 1.5\text{s}$,
- End of the transient at $t = 3\text{s}$.

During the last stage of the transient, sub-assemblies oscillate back at their nominal position. Mechanical models are similar to the steady-state ones, but the influence of the fluid on sub-assemblies motion must be taken into account, as explained in [15].

The power evolution calculated by our two methodologies is given in figure 3. Here again, a good consistency of the results is found, proving the capability of both methodologies to calculate kinetic core distortions.

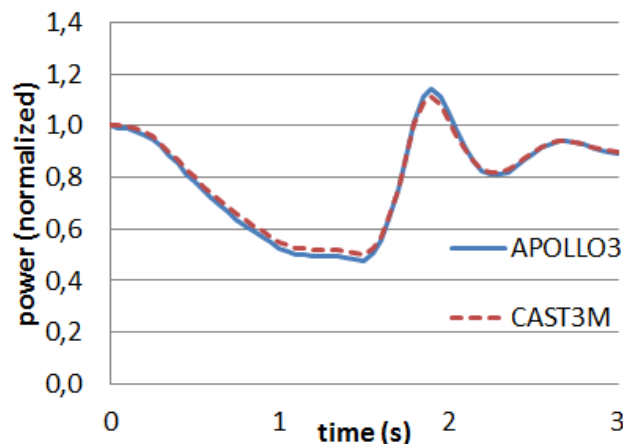


Figure 3. Power evolution during a dynamic flowering of PHENIX core, calculated by APOLLO3[®] with pixelisation technique and CAST3M with deformed mesh.

4. CONCLUSION

A neutronic diffusion solver was developed in CAST3M, a mechanical code, for neutronic calculations of deformed cores. It can greatly simplify and accelerate the data transfers in mechanics-neutronics coupled calculations.

The verification of the solver was done on simple non-deformed cases with APOLLO3[®]. A very good consistency of the results was found, in both steady-state and kinetic. The validity of this tool

to calculate deformed cores was then evaluated on PHENIX flowerings by comparisons with TRIPOLI-4 and with the pixelisation method developed with APOLLO3[®]. Here again, a good consistency of the results was found, in steady-state and in kinetic.

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