EUROFUSION WPBB-CP(16) 15460

G.A. Spagnuolo et al.

Identification of Blanket design points using an integrated multi-physics approach

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Identification of Blanket design points using an integrated multi-physics approach

Gandolfo Alessandro Spagnuolo[a], Fabrizio Franza[a], Ulrich Fischer[a], Virgilio Lorenzo Boccaccini[a]

[a] *Institute for Neutron Physics and Reactor Technology, Karlsruhe Institute of Technology, Hermann-von-Helmholtz Platz 1, 76344, Eggenstein-Leopoldshafen, Germany*

The Breeding Blanket (BB) is one of the key components for a fusion reactor. It is expected to sustain and remove considerable heat loads due to the heat flux coming from the plasma and the nuclear power deposited by the fusion neutrons. In the design of the BB, the engineering requirements of nuclear, material and safety kind are involved. In the European DEMO project, several efforts are dedicated to the development of an integrated simulation-design tool able to perform a multi-physics analysis, allowing the characterization of BB design points which are consistent from the neutronic, thermal-hydraulic and thermo-mechanical point of view. Furthermore, at Karlsruhe Institute of Technology, within the framework of EUROfusion activities, a new research campaign has been launched to set-up this coupling procedure. The first step starts with the definition of the reference geometry, which is converted into a more suitable format for neutronic analysis with Monte Carlo codes. In the second step, the results referred to the calculated power density are properly imported and mapped into an analysis platform based on Finite Element Method. In this study, the Helium Cooled Pebble Bed slice in the equatorial outboard module has been used for the characterization of the procedure.

Keywords: DEMO reactor, Breeding Blanket, multi-physics approach, coupling, design point.

1. Introduction

The design of the Breeding Blanket (BB) represents one of the major challenges for the engineers because of the performance requirements. As a matter of fact, in order to achieve the main functions of the BB several analysis fields have to be investigated during the conceptual design. These functions consist of: 1) recovering the heat generated in the plasma transferring it to the coolant [1], 2) breeding the tritium consumed in fusion reaction [1] and 3) shielding the Vacuum Vessel and superconducting coils from the thermal and nuclear radiation [1]. In particular, the studies commonly involved in the design are of neutronic, thermal-hydraulic and structural kind, which are frequently treated as standalone analyses and where the information flow is user-demanded. For this reason, dedicated coupling simulation tool is needed. Within the framework of the EUROfusion Research and Development (R&D) activities, the Karlsruhe Institute of Technology (KIT) have launched a research campaign dedicated to the development of an integrated simulation-design tool that is able to perform a multi-physics analysis, allowing the characterization of BB design points.

The research activity has been devoted to outline a procedure for the coupling of the well-known commercial software currently used in the design of the BB with the great advantage of deploying the same geometry definition for all the analyses involved. This paper explains the identified coupling procedure that has been characterized using a slice of the Helium Cooled Pebble Bed (HCPB) in the equatorial outboard module. Furthermore, the strengths and weaknesses of this integrated coupling approach are highlighted and the potential developments are described as future steps.

2. The coupling procedure

The proposed procedure for the coupling of neutronic, thermal-hydraulic and thermo-mechanical analysis is articulated in five steps as schematically represented in Fig. 1. The first two steps are aimed to import the investigated geometry from a generic CAD, to decompose it (in order to have a simpler configuration) and to convert it into a format suitable for the Monte Carlo calculations. The third step is devoted to the neutronic analysis in order to assess the neutron flux and the power density deposited into the geometric domain. In the fourth step, the neutronic outcomes are mapped in order to allow a complete integration between the neutronic and finite volume/element codes. In the fifth step, once the thermal-hydraulic and thermo-mechanical calculations have been performed, it will be possible to verify whether the design successfully meets the Code&Standard criteria or a geometry modification should be introduced restarting the analysis cycle.

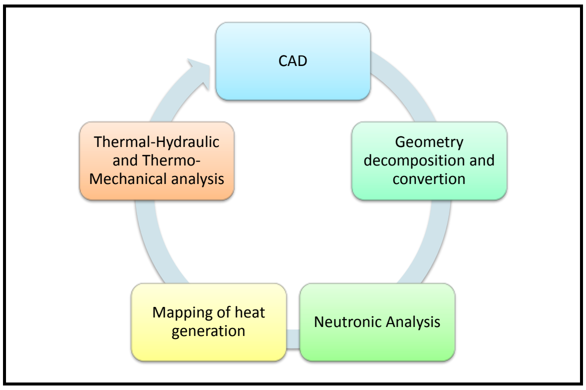

Fig. 1. Schematic of the coupling procedure.

author's email: Alessandro.spagnuolo@kit.edu

3. Geometry decomposition and conversion

For the characterization of the procedure, it has been used, as reference geometry, the slice of the HCPB outboard equatorial module formed by one cooling plate (thickness of 5 mm) and two half pebble beds (7.75 mm for Li_4SiO_4 and 20 mm for Be, respectively). The Breeding Zone (BZ) extends along the radial direction for 520 mm while the Back Supporting Structure (BSS) for 670 mm [2] (Fig. 2a). Once the reference geometry has been imported in ANSYS ModelEditor, it has been sliced in order to have simple configurations that can be easily defined by one and two-dimensional surfaces suitable for the Constructive Solid Geometry (CSG) representation (Fig. 2) [3].

The model has been also provided with the Vacuum Vessel (VV), being composed of three layers (two of stainless-steel and one with homogenized steel and water, 60% and 40%, respectively), the gap between the VV inner wall and the BB, and the cooling channels have been filled so as to model the Helium coolant within the BB.

Furthermore, a domain enclosure [3] has been used in order to shape the Graveyard necessary for the definition of the universe to be analysed in the neutronic analysis (Fig. 2b). The corners of the cooling channels have been squared simplifying the model (Fig. 2a and 2b). This exemplification represents the only difference introduced in the nodalization between the original CAD file and the configuration used for the study.

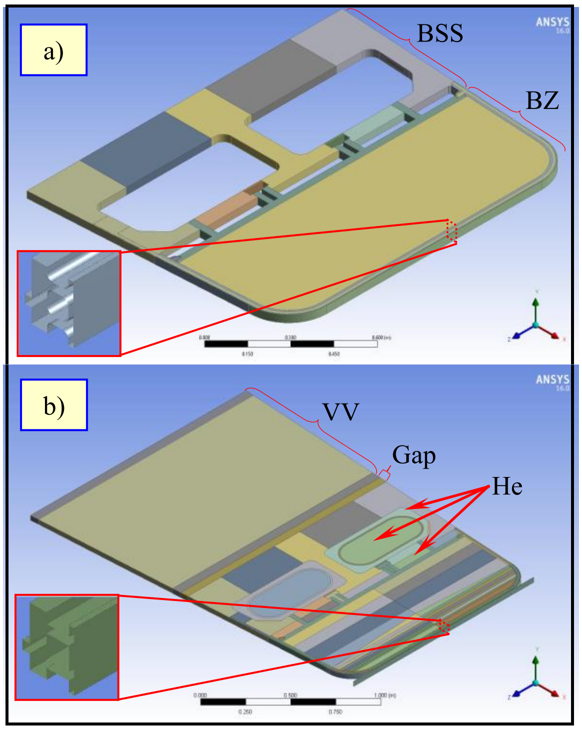

Fig. 2. HCPB slice: (a) original and (b) decomposed model.

Subsequently to the preparation of the model, the elaborated CAD model has been exported using the capability of ANSYS ModelEditor in order to generate a geometric input suitable for neutronic analysis based on the CSG [3]. The main feature of this step is the possibility to have a representation of the geometric domain that is truthful and accurate. Indeed, the channels of the First Wall (FW) and cooling plate as well as the manifolds and the dummy channels have been nodalized avoiding the homogenization of the materials (Fig. 3).

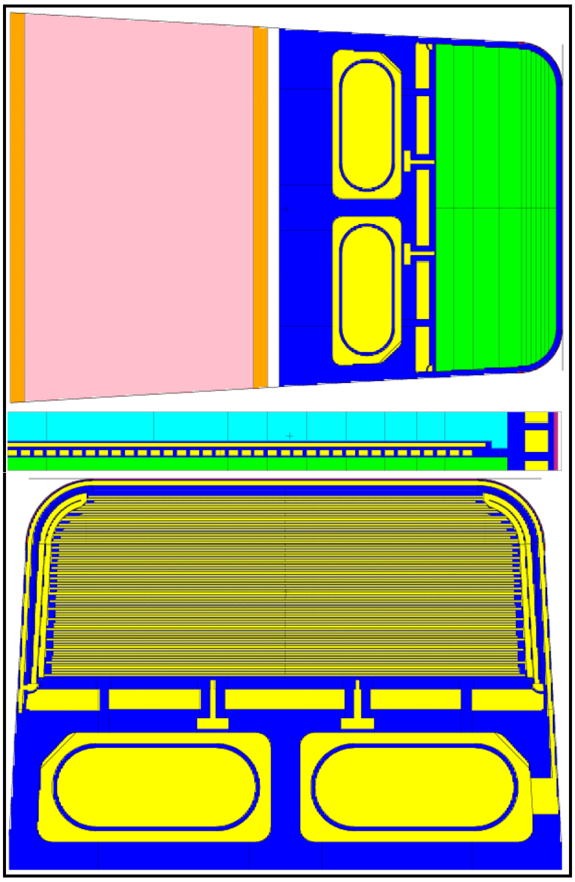

Fig. 3. CSG neutronic model of HCPB slice.

3.1 Geometry verification

The correct definition of the cells and the conservation of the volumes using the stochastic estimation on the ray tracing have been performed [4]. It has been carried out a particle tracing analysis with empty material in order to detect area with multiple surface intersections that will result in tiny interference or empty regions [4]. The errors have been fixed reducing the zone where the particle can be lost.

Furthermore, using the cell flux tally [4], it has been valued the volume of the neutronic models and it has been compared with the reference geometry.

The results have shown an estimation of 5.89470E+04 cm^3 and 5.89403E+04 cm^3 for the ANSYS ModelEditor and MCNP model, respectively, with an overall error of 0.01%. The comparison on the estimated volume has advertised a maximum error comprised between 0.811% and -0.725% for a single cell. The deviation on the volume estimation of the neutronic model from the CAD model has been considered acceptable if lower than 1% and, therefore, the geometry has been successfully verified.

4. Neutronic analysis

Once the geometric input has been prepared and checked, the neutronic analysis has been carried out running 1E+08 particle histories. The boundary conditions and results are hereafter described.

4.2 Neutron source definition

The neutronic analysis has been carried out using a mono-energetic test source biased in the angular distribution. For this reason, a dedicated global reactor model has been developed to simulate the actual neutron volumetric source (e.g. [5]), which is assumed (due to MHD equilibrium properties) to be constant along the plasma magnetic surfaces (MS), as depicted in Fig. 4 with black dashed lines.

Thus, defining radial and vertical profiles for a discrete number of these contours, it is possible to define the volumes included between two nearing MSs ($a_i \leq r \leq a_{i+1}$) and, assuming axial-symmetric condition, between two vertical planes defining a reactor sector.

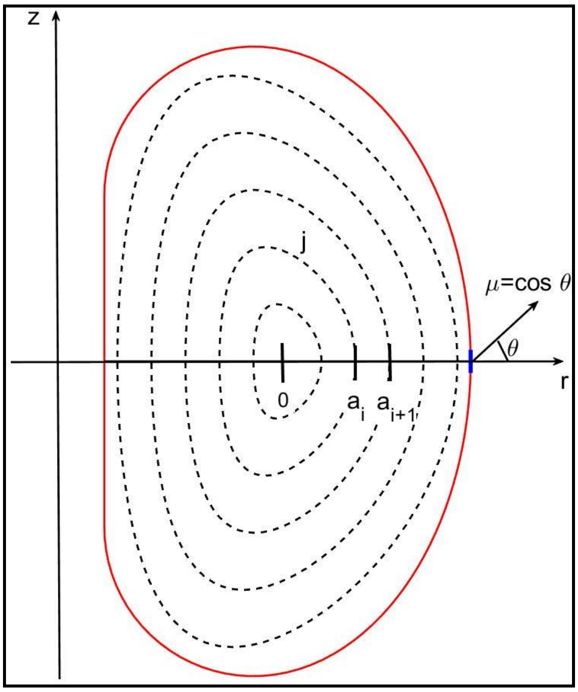

Fig. 4. Global reactor model for neutron source.

The neutron source is therefore sampled on the *j-th* volume (or cell) based on the probability p_j, which is calculated considering a given volumetric source distribution function *S(a)* [5] and it is defined as a volume-averaged value within the related volume domain.

The neutron surface current is tallied for a small wall element identifying the equatorial outboard BB module (blue element in Fig. 4), where the tally F1 has been used with some user-defined bins related to incident angle cosine μ.

The latest is finally used to bias the neutron source deployed in the neutronic simulation for the BB slice.

Void boundary conditions were used for the blanket wall profile (red contour), whilst reflective boundaries were imposed in toroidal direction.

4.3 Boundary conditions

Regarding the modelled HCPB slice, the reflecting boundary conditions have been imposed in the poloidal and toroidal direction, while, for the radial direction, it has been modelled the VV in order to take into account of the neutron back scattering (Fig. 2b and Fig. 3).

4.4 Power density calculation

The power density deposition has been calculated on a superimposed mesh formed by 1.88E+06 elements with a resolution of about 3 mm in x, y and z direction, respectively.

The radial-poloidal-toroidal distribution of the nuclear power density has been assessed (see Fig. 5).

The obtained results, using a simplified definition of the neutron source, display a maximum power density in the Lithium Orthosilicate equal to 10.65 W/cm^3 (Fig. 5).

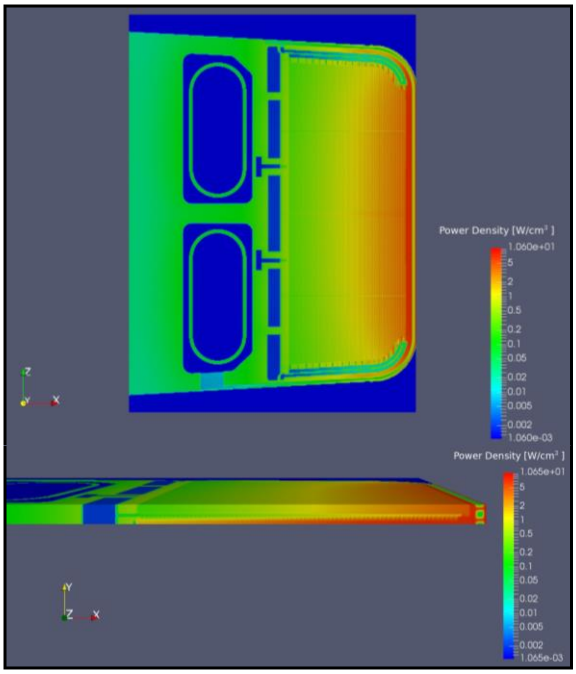

Fig. 5. Power density distribution of HCPB slice.

The statistical precision has been checked for each element of the superimposed mesh; the results have shown that the 99.13% of the mesh elements features a relative error lower than the 5%, the 0.82% comprised between the 5 and 10%, and only the 0.05% greater than the 10%.

The highest errors have been found in the regions far from the neutron source and where the mesh element crosses two cells with different materials like Eurofer (structural material, 9Cr-1W reduced activation ferritic/martensitic steels) and Helium (Fig. 6).

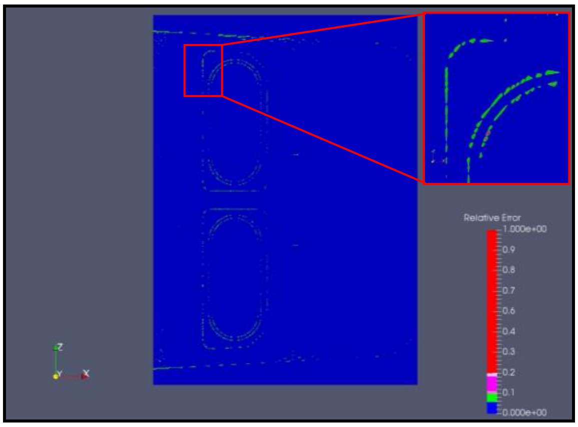

Fig. 6. Relative error on power density distribution.

5. Mapping of heat generation

In order to perform a complete outlining of the power density results into qualified commercial FEM code, a mesh sensitivity analysis has been carried out to determine an appropriated and optimized spatial discretization allowing precise mapping of the neutronic results [3]. A mesh composed of ~6.8E+06 nodes connected in ~2.8E+06 tetrahedral elements has been chosen for the FEM analysis allowing an accurate interpolation of the data between MCNP and ANSYS to be used for the further calculations [3]. The mapping has been performed preserving the profile and using the Distance Based Average that assesses the distance between the target node and the number of closest power density source nodes so as to calculate the weighting value [3]. In order to find the closest points that will contribute with portions of their data values to the map of each target point the triangulation of the data that creates temporary elements (4-node tetrahedrons for 3D meshes) was used [3]. With this final step, a complete coupling has been performed, admitting to use the neutronic outcomes for thermal-hydraulic and thermo-mechanical calculations (Fig. 7).

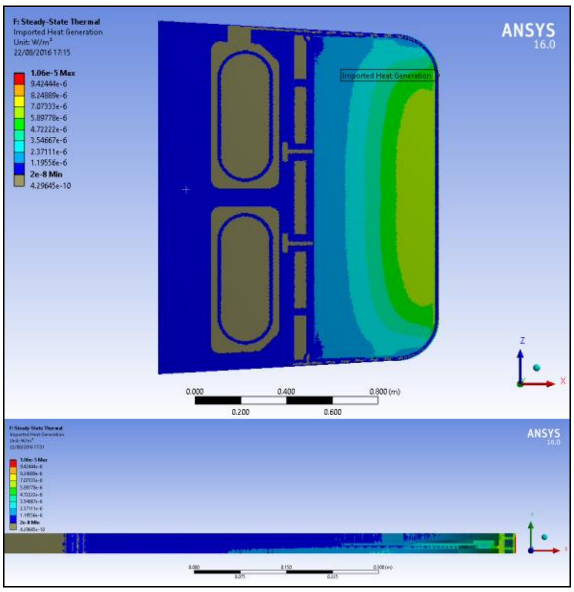

Fig. 7. HCPB slice: mapping of heat generation.

6. Conclusion

A theoretical-computational research campaign is currently being performed at KIT to investigate the possibility to create an integrated multi-physics approach to be used for the identification and analysis of BB design points.

For this study, a test model has been realised using the HCPB slice geometry coming from generic CAD files, which has been converted into more suitable formats for neutronic analysis and then the power density has been calculated, the results have been imported into FEM code accomplishing the complete coupling between the software.

The correctness and applicability of this new approach have been demonstrated, and the great advantages derived from using the same geometry for all the analyses involved in the design of the BB have been also inserted.

As a future potential development, the complete sets of analysis including also the CFD calculation will be implemented and an iterative process will be introduced in order to achieve the optimization of the BB configuration according to the design criteria imposed by Codes&Standards.

Considering the simplifications introduced by the boundary conditions and neutron source definition, several efforts will be dedicated to improve the reliability of the results and a validation campaign will be performed.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] G. Zhou, F. Hernández et al., Preliminary steady state and transient thermal analysis of the new HCPB blanket for EU DEMO reactor, International Journal of Hydrogen Energy, Volume 41 (2016), 7047–7052.
[2] F. Hernández et al., HCPB Design Report 2015 (EFDA_D_2MNBH9).
[3] ANSYS 16.0 Release Documentation.
[4] MCNP - A General Monte Carlo N-Particle Transport Code, Version 5.
[5] C. Fausser, A. Li Puma, F. Gabriel, R. Villari. Tokamak D-T neutron source models for different plasma physics confinement modes. Fusion Engineering and Design 87 (2012) 787–792