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

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HIGHLIGHTS

- The coupling procedure is articulated in five steps.
- The geometry is decomposed and converted for the CSG representation suitable for MCNP.
- The volume conservation is checked using a stochastic volume estimation.
- The power density has been calculated on a superimposed mesh (1.88E+06 elements).
- Neutronic results have been mapped into FEM code performing a complete coupling.

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ABSTRACT

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 characterisation 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 such a 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 the Finite Element Method. The procedure has been successfully tested on a dedicated model (slice) of the helium cooled pebble bed blanket.

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1. Introduction

The design of the breeding blanket (BB) represents one of the major challenges for fusion reactor engineering, mostly because of the performance requirements and technology constraints. 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 [1,2]. These functions consist of: 1) recovering the heat generated in the plasma and transferring it to the coolant, 2) breeding the tritium burnt in fusion reaction [3] and 3) shielding the Vacuum Vessel and superconducting coils from thermal and nuclear radiations [4]. As the BB is a complex multi-physics reactor component, the main R&D campaigns basically involve analyses of different kinds, such as neutronics, thermal-hydraulics [6] and structural mechanics [7]. These are frequently treated as standalone analyses and the information flows is often user-demanded. For this reason, a dedicated coupling simulation tool might ease the overall design process. Within the framework of the EUROfusion programme, Karlsruhe Institute of Technology (KIT) has launched a research campaign for the development of an integrated simulation-design tool capable of performing a multi-physics analysis, potentially allowing the characterisation of BB working points and addressing the key design issues. The ultimate goal, from a pure holistic point of view, is to have at disposal a complete blanket simulation.
platform to understand and overcome the main configuration challenges by interconnecting the whole set of computational analyses. The research activity has been devoted to outline a procedure for the coupling of well-known commercial software currently used in the design of the BB, offering the great advantage of deploying the same geometry definition for all the analyses involved. This article explains the identified coupling procedure that has been characterised using a dedicated model of the helium cooled pebble bed (HCPB) blanket [5]. 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 analyses is articulated in five steps as schematically represented in Fig. 1.

The first two steps aim at importing the investigated geometry from a generic CAD, decomposing it (in order to have a simpler configuration) and converting it into a suitable format for Monte Carlo calculations.

The third step is devoted to the neutronic analysis for the assessment of the neutron and photon flux distributions and spectra, as well as the power density distribution over the considered geometric domain. In the fourth step, the neutronic results are mapped on a mesh geometry in order to allow a complete coupling of the neutronic and finite volume/element codes. In the fifth step, once the thermal-hydraulic and thermo-mechanical calculations have been performed [6], it will be possible to verify whether the design successfully meets the Code & Standard criteria, and if not, proper design modification should be introduced restarting the analysis cycle [7].

3. Geometry decomposition and conversion

The model used as reference geometry for the characterisation of the procedure is a 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 Li₂SiO₄ 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 [5] (Fig. 2a). This geometry is imported in ANSYS Model Editor [8] and then sliced into some simpler configurations easily definable by one and two-dimensional surfaces. The latter are suitable for constructive solid geometry (CSG) representation (Fig. 2b) [8] and can be used as geometric input for the neutronic analyses.

The model has been also provided with an additional layer simulating the presence of the Vacuum Vessel (VV) on the back of the slice. The VV is composed of two pure stainless steel layers (inner and outer) and an intermediate one made of a homogenised steel/water mixture with 60/40% volume composition. Gaps between the VV inner wall and the BB were also included and the cooling channels have been filled so as to model the helium coolant within the BB (Fig. 2b). Furthermore, a domain enclosure [8] has been used in order to shape the Graveyard necessary for the definition of the universe in Monte Carlo analyses and to bind the active volumes of interest [9]. The corners of the cooling channels have been squared to simplify the model (red box in Fig. 2a, b). This represents the only difference introduced in the representation between the original CAD geometry and the configuration used for the study. Subsequently to the preparation of the model, the elaborated CAD model is exported using the capability of ANSYS Model Editor in order to generate a geometric input suitable for Monte Carlo neutronic analyses based on the CSG [8]. The main feature of this step comes from 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 plates as well as the manifolds and the dummy channels have been nodalised avoiding the homogenisation of the materials (Fig. 3).

3.1. Geometry verification

The correct definition of the cells and the conservation of the volumes are checked by means of a stochastic volume estimation based on the ray tracing technique [9]. A particle tracing calculation with empty materials is carried out in order to detect regions with multiple surface intersections that will result in tiny interferences or undefined regions [9]. Such errors are then fixed thus avoiding the geometry regions where particles can be lost during the tracking simulation. In order to evaluate the volumes of the neutronic model to be compared with the reference geometry it has been used the cell flux tally [9]. The results have shown an
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