A multi-physics integrated approach to breeding blanket modelling and design

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Abstract

Often, for the design of a component, several kinds of analyses are needed. Even more frequently, the different fields of study, to be taken into account for the design verification, have to be examined minutely until the final results are satisfying. Furthermore, when geometry modifications are required, for instance to fulfill the component functions, the analyses cycle has to be restarted and an iterative process has to be carried out. This procedure may be time-consuming and herald of errors, in particular if it is demanded to the human activity. Therefore, it is more convenient for the scientific community to adopt a numerical tool that can combine various computational codes. On the base of these considerations, one of the greatest and important challenges for the new design tools is to demonstrate the capability for performing multi-physics analysis in an integrated way. This is a prerequisite, above all, when the component is part of a fusion utility like the Breeding Blanket (BB) in European Demonstration Fusion Power Reactor (DEMO). Indeed, for its design, several fields of analysis are involved such as the neutronics, thermal-hydraulics and the thermo-mechanics. The present work outlines a procedure for their coupling. The main characteristics of this new multi-physics integrated approach are (i) the use of the well-known commercial software, widely employed in the BB design, as well as (ii) the employment of the same geometry definition for all the phenomena studied. An effective application of the aforementioned approach to the pre-conceptual design of the Helium Cooled Pebble Bed (HCPB) and of the Water Cooled Lithium Lead (WCLL) is also provided in this paper. Finally, the achieved results are herewith reported and critically discussed.

Keywords: **multi-physics, coupling, breeding blanket, HCPB, WCLL**

1. Introduction

The European Demonstration Fusion Power Reactor (DEMO) represents one of the most ambitious steps for the realization of fusion reactors able to supply electricity in a safe and environmentally sustainable way [1]. One of the most challenging components of DEMO reactor, from the design point of view, is the Breeding Blanket (BB) [2] [3]. Several technical issues and constraints must be solved and taken into account for the BB design [4]. Among them, the most relevant are: the achievement of a satisfactory efficiency for thermal power conversion, the respect of pumping power requirements, the problems related to the thermal power handled by the First-Wall (FW), the neutron shielding requirements, the achievable Tritium Breeding Ratio (TBR) and the tritium permeation issues into the coolant [5] [6]. The technical issues are linked to each other and the solution of one can compromise or make worse to find a solution for another one, especially when the problems are investigated separately. Moreover, the common coupling procedures, applied in the BB design, are usually performed manually and the geometries used for each study are different [7]. Lastly, when geometry modifications are required during the thermal-hydraulic and structural analyses, often the changes are not reported back and applied to the neutronic one. For these reasons, the necessity to develop a multi-physics approach that allows a holistic investigation of all the analysis fields is becoming increasingly pressing in the fusion community. In this sense, many efforts have been dedicated to the development of systems codes for the assessment of the main design parameters of DEMO reactor [8] [9]. Considering the complexity of the phenomena investigated, these codes have to introduce simplifications in the phenomena modelling and in the degree of detail used for the geometry representation. Therefore, the outcome, given to the designers, usually represents a gross estimation of the layout useful only to establish the limit of action or the magnitude range of performances. For sure, these preliminary results are valuable in the early stage of the DEMO conception, but not when the final design is approaching and more details are required. In this framework, it is increasingly clear the necessity to use a multi-physics integrated approach for the analyses deploying the same geometry definition for all the studies. The research activity, herewith described, has been aimed to outline a new multi-physics integrated approach for the coupling of well-known commercial software, starting and sophisticating the procedure already described in [10]. In this paper the following tasks are described: the multi-physics integrated approach for the coupling procedure (paragraph 2), the methodologies for the automatic conversion of CAD geometries in neutronic inputs (paragraph 3), the boundary conditions applied for the neutronic calculation and the results obtained (paragraph 4), the preliminary thermal-hydraulic and thermo-mechanical results and their implication on the final design (paragraphs 5 and 6).

2. The multi-physics integrated approach

The multi-physics integrated approach, herewith proposed, aims to the direct coupling between the neutronic, thermal-hydraulic and thermo-mechanical calculations using MCNP5/6 [11] [12] and ANSYS [13], respectively. The research campaign focused on the sophistication and the improvement of the preliminary coupling procedure proposed in [10]. Additional steps and sub-steps have been identified as reported in Figure 1. Starting from the geometry definition (a), the latter is decomposed and converted (b) in a format that is suitable for neutronic analysis. Two different methodologies are developed for the direct creation of the neutronic input using ANSYS, one based on Constructive Solid Geometry (CSG) representation [10] and the second one on the hybrid geometry definition where the Unstructured Mesh (UM) is embedded into the CSG model [14]. Once the neutronic model is created within ANSYS, it is checked by means of the stochastic volume estimation and the neutronic analysis (c) is performed. Defining a proper neutron/photon source and boundaries conditions, it is possible to calculate the 3D profile of the power density (c.1). Afterwards, the heating distribution is mapped (d) into Finite Volume Method tool like CFX (currently the most used tool for the thermal-hydraulic design of the BB) and the fluid-dynamic calculation is carried out (e). Then, the thermal-hydraulic parameters are checked and, if the requirements are satisfied, it is performed the thermo-mechanical analysis (f), otherwise the geometry has to be modified and the procedure restarted from (a). Subsequently, the criteria coming from Code&Standard (C&S) are checked in order to verify the compliance of the design (g). In the following paragraphs, each step of the new multi-physics integrated approach will be described in more detail.

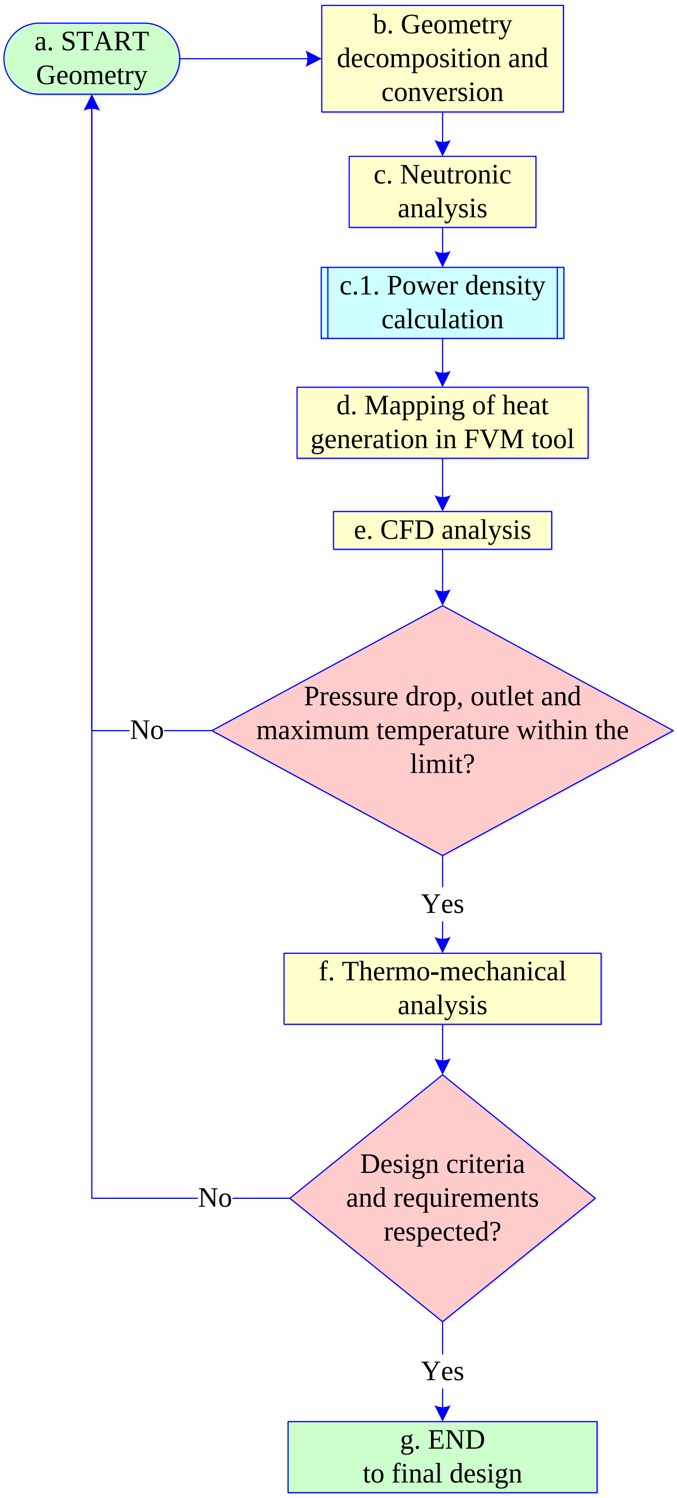

Figure 1. Multi-physics integrated approach flow chart.

3. Geometry decomposition and conversion

Two different methodologies have been identified and investigated for the automatic generation of an input suitable for the neutronic analysis. The first is based on the CSG representation where the geometrical regions are defined by means of first and second degree surfaces [11]. The second one is based on UM embedded in the legacy CSG to create a hybrid geometry representation. Henceforth, the two methodologies will be indicated as *CSG*

Modelling and *Hybrid Modelling*. The *CSG Modelling* has been applied to the slice [10] and to the cap of the outboard equatorial module of the Helium Cooled Pebble Bed (HCPB), while the *Hybrid Modelling* to the slice of the outboard equatorial module of the Water Cooled Lithium Lead (WCLL) because the two geometries investigated (helical and serpentine tubes, Figure 3) would not be easily represented using the *CSG Modelling*.

3.1. CSG Modelling

The *CSG Modelling* has been already introduced in [10] for the nodalization of the HCPB slice. The same methodology has also been successfully applied to the solid model of the cap [15] of the outboard equatorial module as reported in Figure 2. Together with the neutronic model of the HCPB slice, it has been used for the creation of the full equatorial outboard module adopted for the preliminary validation of the boundary condition and of the neutron/photon source definition applied for the neutronic analysis. A detailed explanation of the validation results can be found in [16].

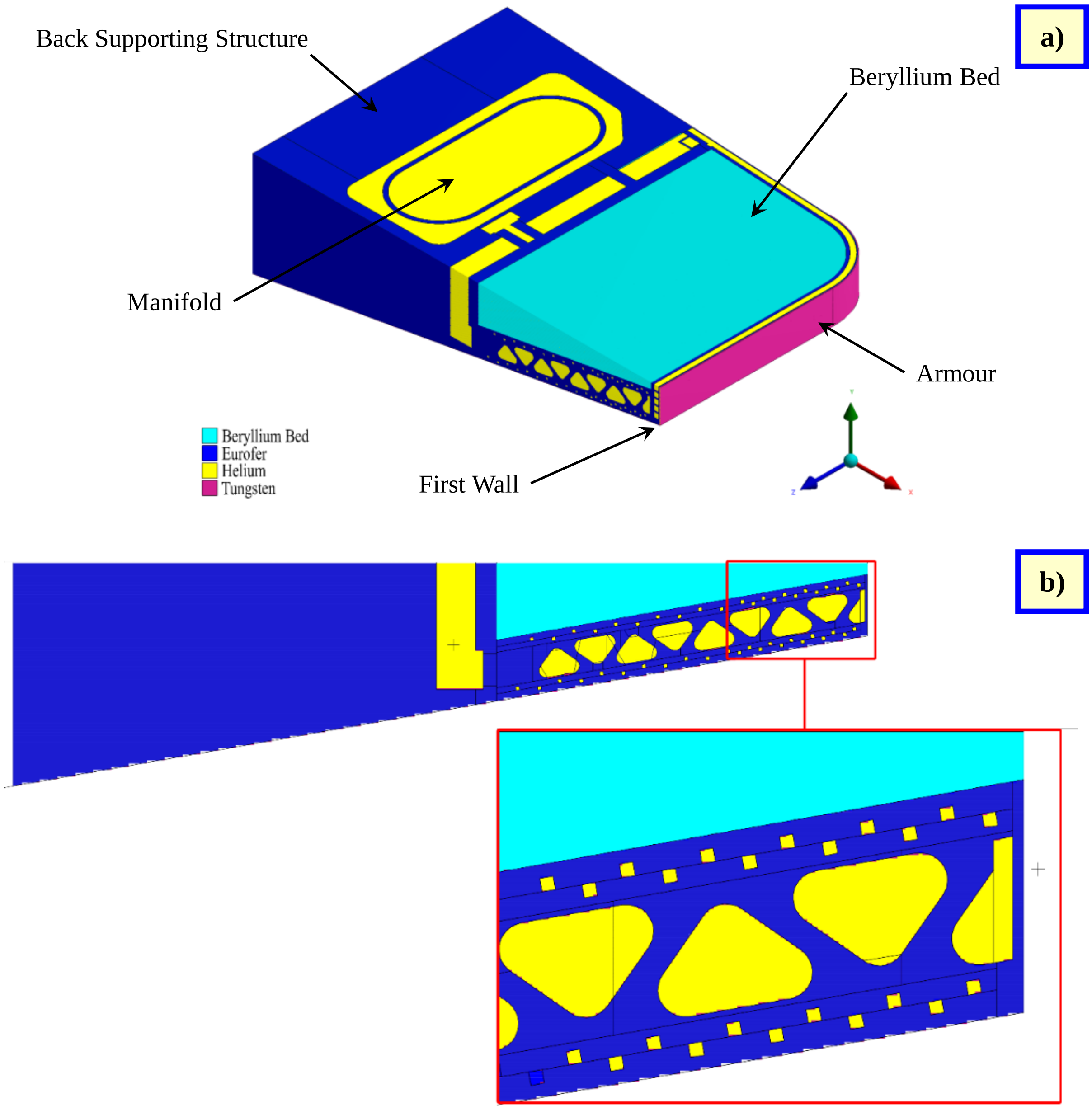

Figure 2. HCPB cap: (a) original and (b) decomposed model [16].

3.2. Hybrid Modelling

MCNP6 addresses the possibility to embed an unstructured mesh (UM) representation of a geometry in its legacy CSG to create a hybrid representation. The UMs, such as those created by the Finite Element code ABAQUS/CAE [14], can be directly imported into MCNP6 allowing a more precise layout definition in the neutronic model. The originality of this research campaign consists in using ANSYS capability rather than ABAQUS/CAE for generating the UM input suitable for MCNP6. This methodology allows a complete coupling between MCNP6 and ANSYS affording the realization of an integrated multi-physics design tool able to perform neutronic, thermal-hydraulic and thermo-mechanical analysis based on the same geometry. The *Hybrid Modelling* has been applied for the simulation of two different configurations of the WCLL Breeder Zone (BZ). One with 6 poloidal helical tubes ([17] and [18]), one for each breeder unit, and the second one with 12 serpentine tubes routed in radial-toroidal direction, two for each breeder unit, as shown in Figure 3. For the two cases, each domain has been subdivided in parts and meshed [19], as reported in Figure 4. For both cases, 18 parts or pseudo-cells [14] have been created with an overall amount of ~9.00E+05 elements for the helical configuration and ~9.28E+05 for the serpentine one, respectively [19].

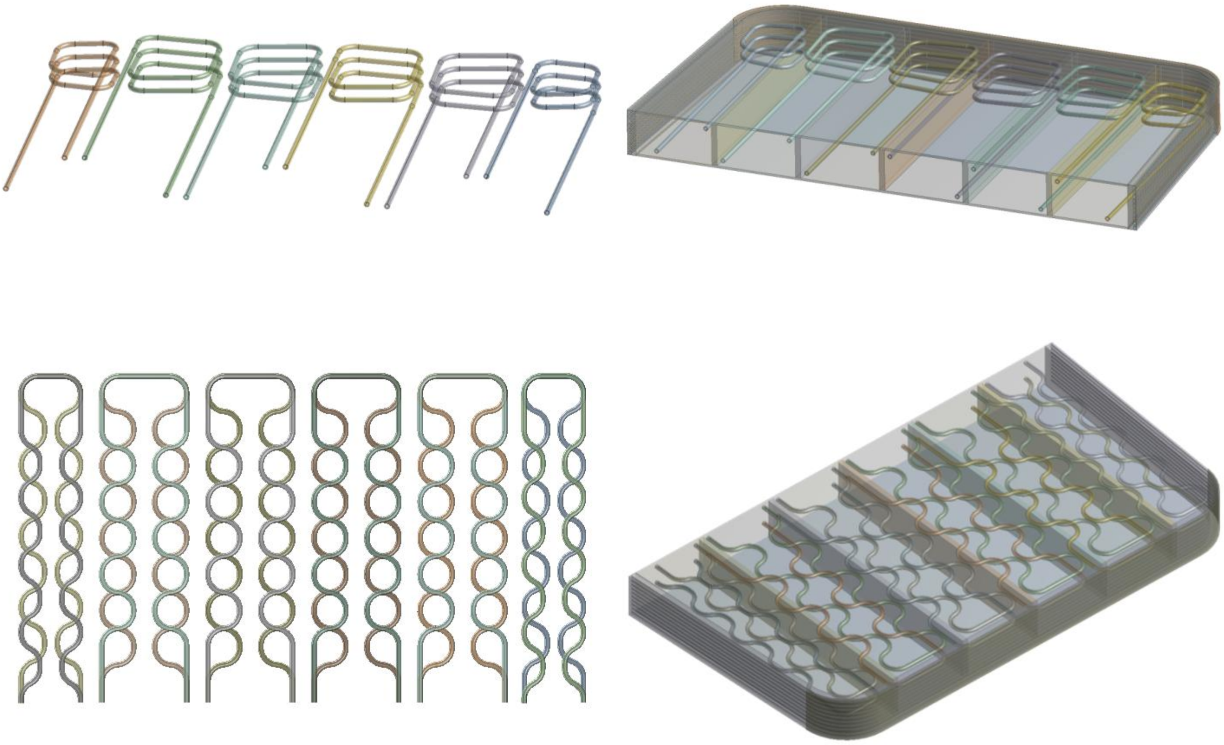

Figure 3. WCLL BZ: helical tubes (top) and serpentine tubes (bottom) layout.

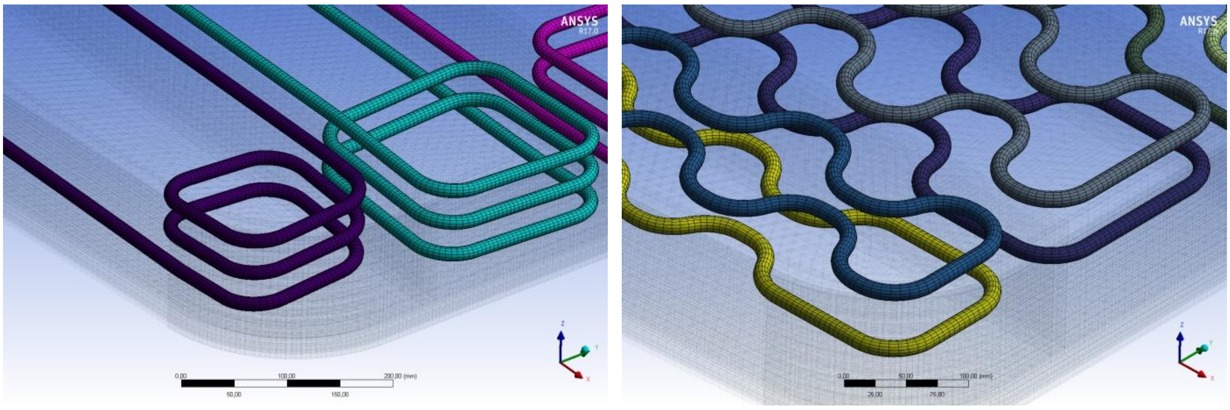

Figure 4. WCLL BZ: UM helical tubes (left) and UM serpentine tubes (right).

Using ANSYS capabilities and specific in-house scripts, the different part meshes have been translated in ABAQUS/CAE language constituting by parts, element set, assembly and instance as required in [14]. Furthermore, the ANSYS capability to create a WCLL neutronic model, based on the CSG geometry representation where the UM can be embedded, has been used. Thanks to the *Hybrid Modelling*, it has been possible to represent these "*exotic*" layouts in MCNP6 that, otherwise, it would not be possible to reproduce with *GSG Modelling* without to introduce geometry simplifications such as homogenizations. The two completely heterogeneous neutronic models are shown in Figure 5 [19].

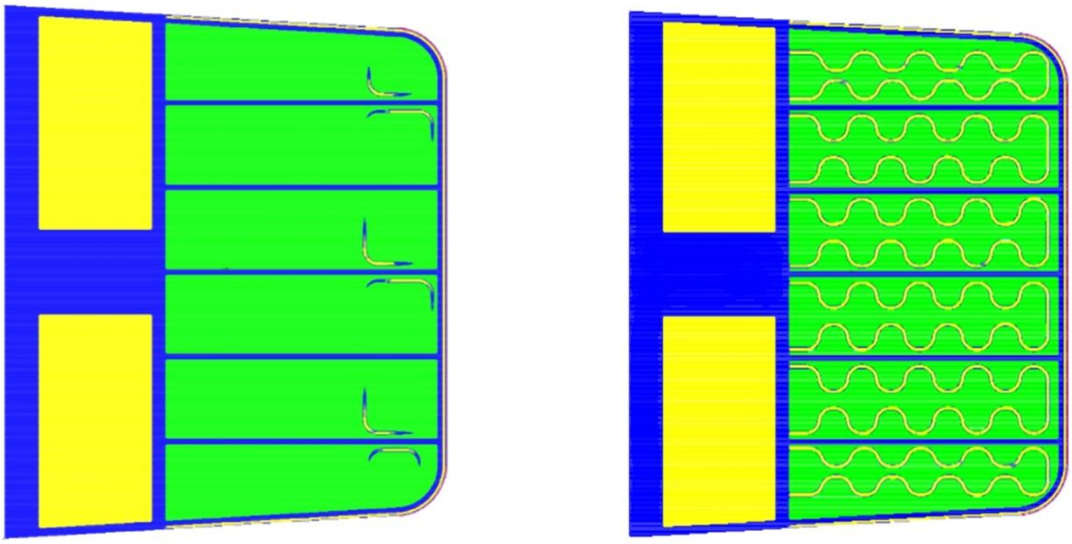

Figure 5. WCLL BZ: helical tubes (left) and serpentine tubes (right) neutronic model.

The correct definition of the cells and the conservation of the volumes have been checked in order to demonstrate that the neutronic model represents faithfully the real geometry. For this purpose, the *stochastic volume estimation* has been used in order to evaluate the volumes of each cell and the results have been compared with the volumes calculated using ANSYS ModelEditor. For the helical configuration, the overall error on the volume estimation between ANSYS ModelEditor and MCNP6 models is equal to -0.004%. The comparison of the estimated volumes of single cells has shown a maximum deviation between 0.074% and -3.656%. The main difference has been found in the helical channels where a coarse mesh has been used in order to stay within the element number limits for each part (about 50.000 elements per pseudo-cell [12]). This issue has been solved in the serpentine configuration using second-order pentahedra and hexahedra elements. Therefore, for the serpentine layout, an overall error of -0.0005% has been found with a maximum deviation between 0.0021%

and -0.0068% for the single cells. For both cases, an overall volume deviation less than 1% has been considered acceptable and, therefore, the geometries have been successfully verified [19].

4. Neutronic analysis

For both the HCPB slice, based on *CSG Modelling*, and for the WCLL slice, based on *Hybrid Modelling*, a neutronic analysis has been performed. For determining the local neutron/photon source to be used for the neutronic analysis of the HCPB and WCLL slices, the global MCNP model of DEMO has been used [20] and a surface corresponding to the outboard equatorial module where the neutrons are biased in cosine and energy has been identified. The cosine distribution has been ranged in 10 subdivisions while the neutron energy has been sampled from 0.111 MeV to 14.2 MeV subdivided into 98 energy bins and the photon energy has been sampled from 0.001 MeV to 50.0 MeV subdivided into 43 energy bins, in agreement with [21]. Then, the cumulative probabilities of a neutron and a photon emitted in a determinate angle with a certain energy bin have been calculated. In this way, it has been possible to take into account the albedo effect of the reflected neutrons and photons, and to have a good estimation of the local neutron and photon source to be used for the calculations on the slices. In the local neutronic model of the HCPB and WCLL slices, reflecting boundary conditions have been imposed in poloidal and toroidal direction, while, for the radial direction, the VV has been included, as explained in [10]. The results, for both cases, have been normalised to the total neutron yield taking into account the ratio between the source surface of the local model and the equatorial outboard area of the global model where the source has been sampled. For the HCPB slice based on *CSG Modelling*, the power density deposition has been calculated on a superimposed mesh of 1.88E+06 voxels with a resolution lower than 3 mm in x, y and z direction (Figure 6, left). The 99.13% of the 1.88E+06 mesh elements have a relative error lower than 5%, 0.82% between 5 and 10%, and only 0.05% greater than the 10% (Figure 6, right). Due to the superimposition of a structured mesh on the cell definition when the *CSG Modelling* is used, an overlap of the voxels on two different materials can occur. This represents the main drawback of the *CSG Modelling* respect to the *Hybrid Modelling* where the issue has been completely solved meshing each domain separately but at the expense of greater computational effort (the calculation time may increase up to the ~50% more when the *Hybrid Modelling* is used instead of *CSG Modelling*).

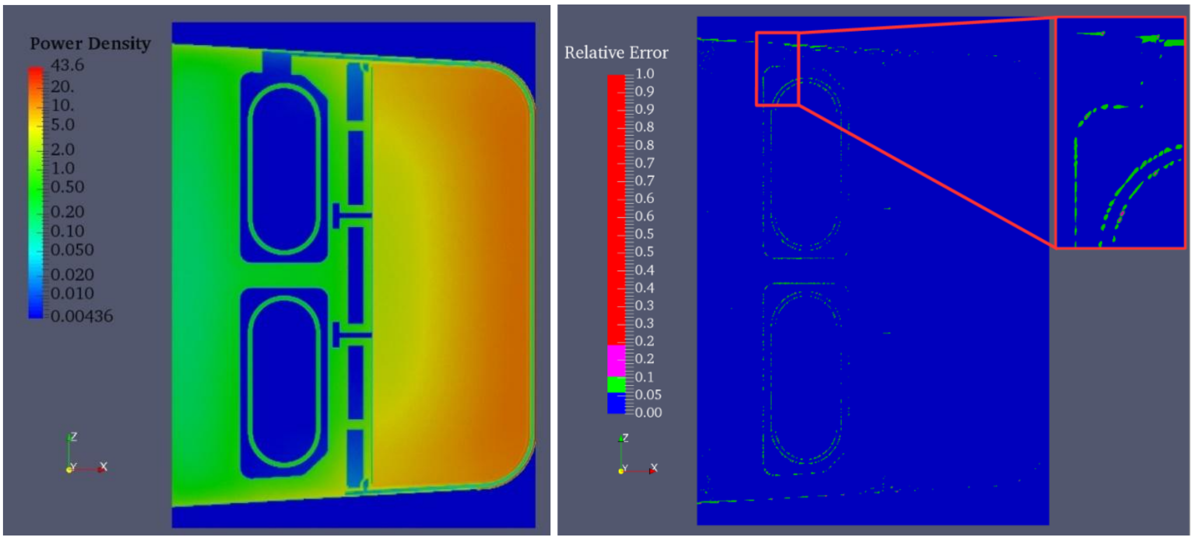

Figure 6. HCPB slice 3D power density (left) and relative error (right).

As an example of the results obtained by the model, the power density calculation is shown on the serpentine tubes configuration (Figure 7, left). The 89.42% of the mesh elements have a relative error lower than 10%, 8.03% between 10 and 20%, and 2.55% with an error greater than 20% (Figure 7, right). Considering that no variance reduction techniques have been used and taking into account that for a relative error lower than 10-20% the results are considered reliable except for a point detector [11], these preliminary outcomes are a credible estimation of the power deposited in the WCLL. The introduction of variance reduction techniques could mitigate high relative errors. After a careful analysis of the elements with a relative error greater than 10%, it has been noted that there is an indirect proportionality between the element size and the error therewith associated. The distance from the neutron source plays also a relevant role in the accuracy of the results.

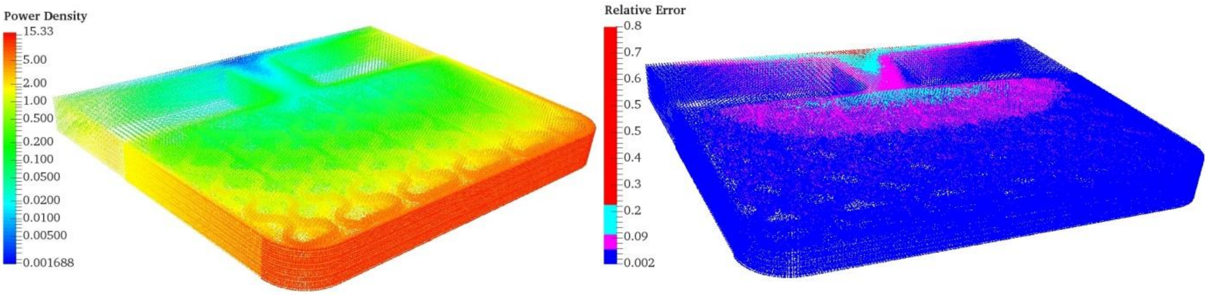

Figure 7. WCLL slice 3D power density (left) and relative error (right).

Both modelling techniques demonstrate their effectiveness in the representation of complex geometries providing useful information for the development of the design. Thanks to the application of these methodologies, it is possible to highlight issues that otherwise could be hidden by the simplification introduced. For instance, it is easily noted that there are neutron streaming problems on the side walls of the BB which shall handle a higher power density.

5. Mapping of heat generation and CFD analysis

Once the neutronic analyses, using the *CSG and Hybrid Modelling*, have been performed, the coupling methodology has been further tested pursuing the CFD calculations. The mapping of the power density has been performed as reported in [10]. It is important to underline that the neutronic and the CFD models are the same from a geometric point of view, so the error associated with the heating interpolation is limited to the differences in the meshes. This represents the only deviation. The boundary conditions for the thermal-hydraulic calculations are the ones reported in [15]. In particular, adiabatic conditions on the sides and back of the BB, symmetry conditions in the poloidal direction and a constant heat flux of 0.5 MW/m^2 on the FW.

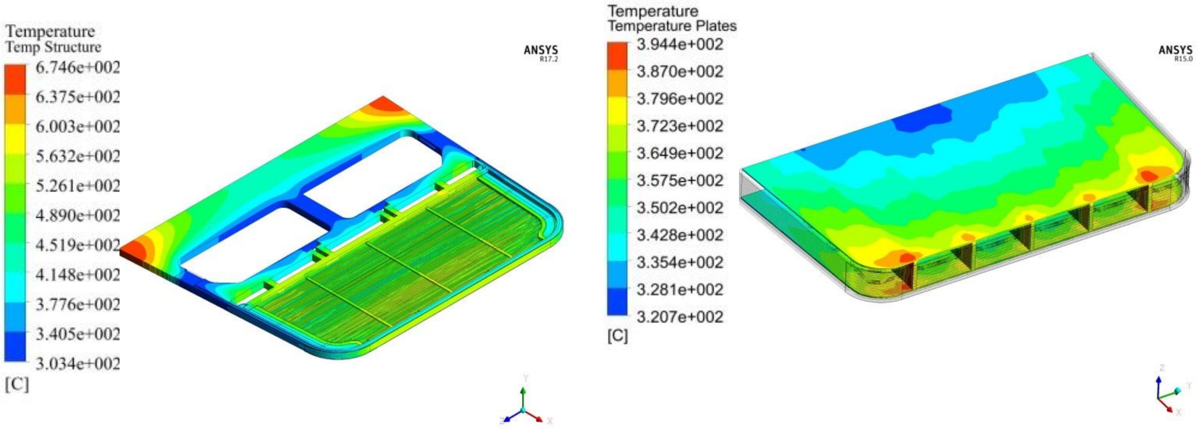

Figure 8. HCPB temperature field (left) and WCLL temperature field (right).

The preliminary results show that, according to the power density distribution obtained from the neutronic calculation, the BB side walls are strongly loaded (Figure 8). Therefore, in the case of HCPB, the temperature limit of 550°C on the structural material (EUROFER) is not respected in the rear of the slice (Figure 8, left). It means that a different cooling layout should be foreseen in that region. These preliminary outcomes have to be interpreted as first attempt but also as an important test for demonstrating the effectiveness of the multi-physics integrated approach herewith proposed.

6. Thermo-mechanical analysis

As an example of the results obtained by the model, the thermo-mechanical calculation is shown on the HCPB slice configuration. Although the thermal-hydraulic results obtained for the HCPB slice show a maximum temperature over the limit, it has been decided to continue with the application of the integrated multi-physics approach in order to demonstrate the effect on the final evaluation. Indeed, according to the flow chart reported in Figure 1, when the thermal-hydraulic limits are not respected, a design modification should be introduced.

Once the temperature field has been assessed, it can be mapped for performing structural analysis in order to determine the stresses and to verify the compliance with the C&S criteria.

The boundary conditions in normal operation (static) are the ones reported in [15] and [22]. In particular, symmetry and plane deformation have been applied in the poloidal direction while radial and toroidal displacement has been prevented for the nodes lying in the toroidal and poloidal direction at the rear of the BB. In the cooling channels, a pressure of 8 MPa has been imposed and the temperature profile obtained from CFD calculation has been considered [15].

The preliminary results, in terms of equivalent Von-Mises stress field, (Figure 9) show that the back of the HCPB slice and some regions located near the manifolds fail by plastic collapse and instability. According to these results, a different cooling layout should be implemented in the rear of the HCPB while a more flexible structure will have to be considered between the manifolds.

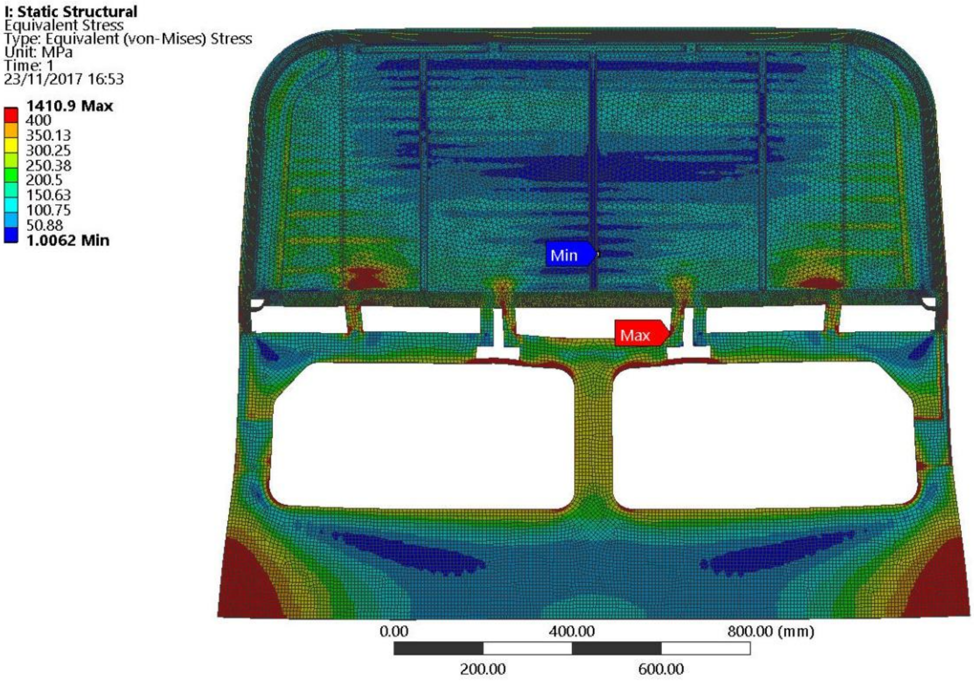

Figure 9. HCPB equivalent Von-Mises stress field.

Conclusions

Several efforts have been dedicated for the development of a coupling methodology that is able to:

(i) evaluate neutronic variables useful for thermal-hydraulic and thermo-mechanical analyses (power density distribution in operational material, neutron wall load profile, etc.).
(ii) make a screening of thermal-hydraulic design points (pressure drop, channel velocity, mass flow rate, temperature, etc.)
(iii) verify the stress field against the C&S design criteria.

Satisfactory results have been achieved using the ANSYS capability to generate both CSG and hybrid geometry representations suitable for neutronic analysis. The developed methodology not only represents a new methodology for the design, but has also demonstrated a coupling versatility with a good estimation of the power deposited on the BB as well as an extremely precise power density profile calculation. Furthermore, efforts have also been dedicated to the development of specific scripts in order to speed-up the coupling procedure simplifying the data transmission between ANSYS-MCNP-ANSYS. With this preliminary multi-physics integrated approach, the benefits related to the use of the same geometry for all the investigations have been demonstrated, allowing the detection of a design issue that, otherwise, would be hidden by the model simplification. This fact, linked to the use of codes like ANSYS and MCNP, may represent a great advantage for the designers and for the speed-up of the analysis process.

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