Fusion Engineering and Design 124 (2017) 940–943

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Automated parametric neutronics analysis of the Helium Cooled Pebble Bed breeder blanket with $Be_{12}Ti$

J. Shimwell[a,*], L. Lu[b], Y. Qiu[b], P. Pereslavtsev[b], A. Häußler[b], F. Hernández[b], C. Zeile[b], T. Eade[a], G.A Spagnuolo[b], S. McIntosh[a], L. Packer[a], T. Barrett[a]

[a] Culham Centre for Fusion Energy (CCFE), Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK
[b] Karlsruhe Institute of Technology (KIT), Karlsruhe, Baden-Wurttemberg, Germany

ARTICLE INFO

Article history:
Received 2 October 2016
Received in revised form 5 January 2017
Accepted 9 January 2017
Available online 1 March 2017

Keywords:
Fusion
Breeder blanket
Neutronics
Volumetric heating
HCPB
Coupled
Parametric
CAD

ABSTRACT

The Helium Cooled Pebble Bed (HCPB) breeder blanket is being developed as part of the European Fusion Programme. Part of the programme is to investigate blanket designs relevant for future demonstration fusion power plants. This paper presents neutronics analyses of the HCPB with an alternative neutron multiplier, $Be_{12}Ti$ which is incorporated into the design, replacing the current Be multiplier. A parameter study was performed for a range of geometries to identify the optimal heights of the lithium ceramic and neutron multiplier pebble beds. Automated creation of CAD models followed by conversion to constructive solid geometry (CSG) and unstructured mesh (UM) geometry allows the models to be useful for both neutronics simulations and engineering simulations. In this neutronics study simulations were performed using MCNP 6.1 to find the tritium breeding ratio, energy multiplication and the volumetric heat loads of different blanket designs. Combinations of geometry parameters and material choices that resulted in adequate TBR values were identified and will be further investigated with automated engineering simulations. This paper provides insight, supported by neutronics analysis, on the validity of the design and comments on some of the potential advantages and disadvantages of using $Be_{12}Ti$ in the Helium Cooled Pebble Bed (HCPB) breeder blanket. Blankets with $Be_{12}Ti$ neutron multiplier were found to produce less tritium but higher energy multiplication when compared to blankets with Be neutron multiplier.

© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Optimising the design of components for use in future power producing fusion reactors requires a combination of analysis techniques. This paper presents an automated procedure for coupling neutronics and engineering analysis and findings from a demonstration neutronics study. The neutronics performance of two different neutron multipliers ($Be_{12}Ti$ and Be) is compared. Potential benefits of switching from Be to $Be_{12}Ti$ are: reduced swelling, reduced tritium retention and higher temperature limits [1].

Neutronics analysis is used to calculate important performance metrics for breeder blankets such as: the tritium breeding ratio (TBR), energy multiplication (the ratio of energy incident on the blanket to energy released in the blanket) and volumetric heating. While it is possible to rule out designs which fall short of the neutronic requirements (e.g TBR>1.1) it is necessary to perform further analysis to assess the suitability of designs in terms of other important attributes.

Engineering analysis techniques such as finite element analysis can be used to further assess design suitability. Thermal hydraulics and structural mechanics analysis are able to utilise outputs of neutronics analysis (e.g. volumetric nuclear heating) and obtain additional performance metrics such as the temperature and stress within components.

The design process is iterative and involves several steps beyond neutronics and engineering simulations. However coupling neutronics and engineering simulations so that designs can be assessed across disciplines can streamline a significant part of the design process. The volumetric heating resulting from this simulation is provided with the intention of further use in FEA codes and currently the eeout file produced by MCNP is converted to VTK for visualisation and Ensight Gold format for use in ParaFEM [2].

There are inherent difficulties in coupling the two disciplines such as the difference in geometry used by the two disciplines. Neutronics analysis within fusion research is typically performed using the Monte Carlo (MC) method and constructive solid geometry

* Corresponding author.
E-mail address: mail@jshimwell.com (J. Shimwell).

http://dx.doi.org/10.1016/j.fusengdes.2017.01.004
0920-3796/© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

(CSG); whilst finite element analysis relies on CAD geometry and utilises meshes generated from Boundary Representation (BRep) geometry. Unfortunately simulating MC particle transport on BRep geometry is not currently mature.

Traditionally neutronics simulations have utilised structured meshes to tally volumetric heating. Unfortunately structured meshes do not conform to the geometry and this tends to result in single mesh elements containing multiple materials, which in turn results in loss of data fidelity.

Recent improvements in MCNP 6.1 [3] allow particle transport and tallying on unstructured meshes that conform to geometry and material boundaries. This opens up the possibility of performing neutronics and engineering analysis on the same underlying CAD geometry.

Similar methodologies have previously been suggested [4] and this research represents an earlier application of the unstructured mesh and parametric CAD based neutronics studies for optimising fusion reactor components.

2. Method

The approach taken in this paper is to generate CAD geometries parametrically that can be used by neutronics and are compatible with engineering analysis.

CSG geometry is well suited to neutronics simulations and metrics such as TBR and energy multiplication can be readily obtained using CSG geometry. These results will be used to assess the neutronics performance of a particular design and will not be utilised by engineering analysis. The CSG geometry used to obtain TBR and energy multiplication can be created by converting from the base CAD model to CSG. This was performed using McCad which is able to decompose STEP files and convert to CSG inputs files for a variety of MC-code [5]. Care was taken during the construction of the CAD geometry to avoid the use of spline surfaces to describe BRep solids, this facilitates the CAD to CSG conversion process as spline surfaces are not supported in CSG. Recent improvements to McCad allow separate CAD solids to be converted into CSG geometry and grouped as single cells.

Volumetric nuclear heating caused by neutron and photon interactions is also calculated by neutronics simulations. In this case the output from the neutronics simulation is required as an input for engineering simulations which require spatial variation. Therefore this metric has been simulated using unstructured mesh geometry which can be used directly in engineering simulations. This approach reduces the need for interpolating results between dissimilar geometries and reduces the opportunities for errors when translating between the two simulation techniques.

A pre-existing CAD model of the 2015 EU DEMO with empty blanket boxes developed within the Power Plant Physics and Technology (PPPT) programme [6] was used as a template into which detailed blanket models could be inserted. The EU DEMO model was converted into CSG geometry using McCad for later use.

Parametric CAD models of the breeder blanket internal layout were generated using Python programmes and SALOME 7.8.0 [7]. Available geometric parameters include: cooling plate height, pebble bed height for the lithium ceramic and pebble bed height for the neutron multiplier. Fig. 1 shows two examples of parametrically produced breeder blanket designs.

Traditional CSG neutronics simulations were performed to calculate the TBR and energy multiplication. First McCad terminal commands were used to decompose and convert the CAD geometry into CSG geometry. The solids belonging to each different material were counted and grouped prior to exporting the geometry to a STEP file format. This ensured that the generated MCNP input file contained cells arranged by material. It was therefore possible to automatically assign the correct materials to the separate MCNP cells.

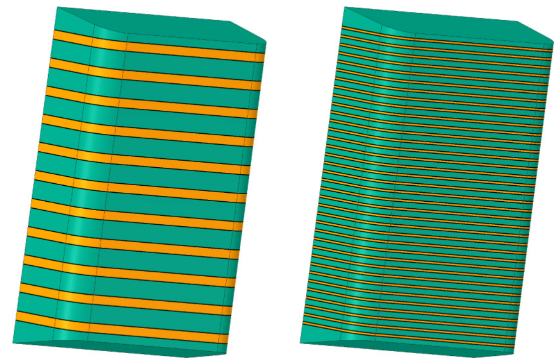

Fig. 1. An example of two breeder blanket designs with different parameters. The lithium ceramic (yellow), cooling plates (black) and neutron multiplier (turquoise) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Material densities and material cards were produced via Python a programme to match the user requirements. The design tool was constructed to allow a variety of different lithium ceramics and neutron multipliers. For this paper the lithium ceramic was Li_4SiO_4 enriched to 60% ^{6}Li and models with both $Be_{12}Ti$ and Be neutron multipliers were constructed. All pebble beds were assumed to have a packing fraction of 0.63. The design tool is flexible and can produce models for different functional materials (e.g. Li_2TiO_3 or $Be_{12}V$) provided that the density is known (Fig. 2).

A tally was added to the MCNP input file to calculate the TBR for the blanket design (see Fig. 4). A tally was also added to calculate the energy deposited by neutrons and photons within the breeder blankets (see Fig. 5).

The newly created detailed MCNP geometry of the blankets along with the material definitions and tallies were combined with the pre-existing EU DEMO design to produce a finished geometry (see Fig. 2). A hybrid (GSC and UM) approach was used to calculate volumetric heating within the breeder blanket slice. Individual

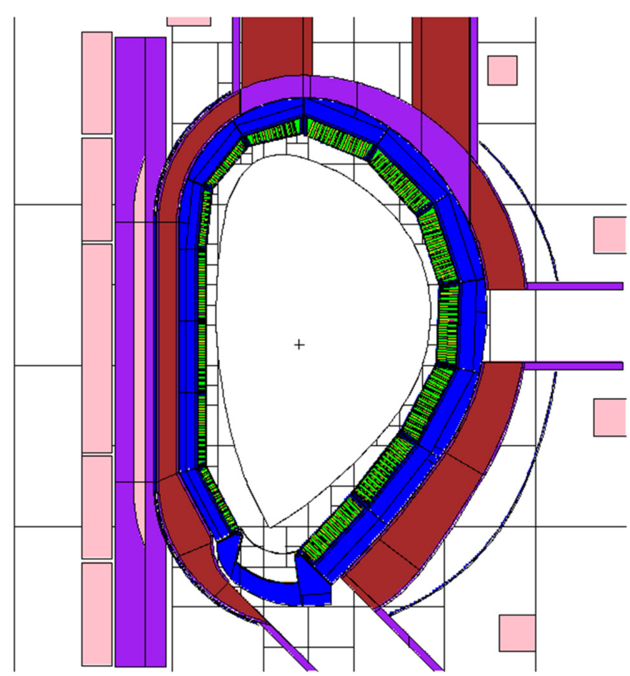

Fig. 2. The tokamak model used was adapted from a DEMO model developed within the PPPT programme [6].

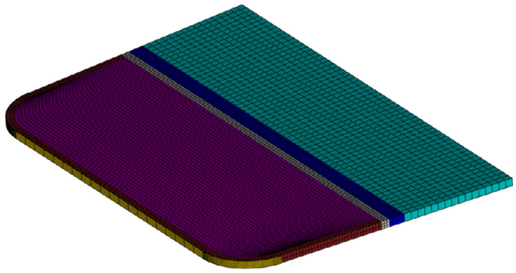

Fig. 3. Hexahedral mesh HCPB breeder blanket slice showing the tungsten armour (yellow), Eurofer first wall (red), lithium ceramic (purple), rear blanket casing (grey), shielding (blue) and the blanket coolant supply (turquoise). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

layers of lithium ceramic, neutron multiplier and a coolant plate were extracted from the middle of the equatorial outboard blanket module. The lithium ceramic and neutron multiplier layers were reduced in height by 50%, this was done to facilitate the creation of boundary conditions for engineering simulations.

To further facilitate planned engineering simulations it was necessary to construct an entire slice of the breeder blanket, including the first wall, rear casing and shielding. To achieve this the cooling plate, along with the reduced height lithium ceramic and neutron multiplier layers were fused together. The upper and lower surfaces of this fused geometry were then used as a cutting plane to divide up the first wall and rear components.

The resulting parts belonging to the slice were all fused together to form a single solid which would serve as a bounding box for the unstructured mesh geometry. The individual slice components were automatically meshed using Python programmes and Trelis 16.1 [8]. The density of the different materials was incorporated into the mesh by passing APREPRO variables as command line arguments to Trelis. When converting from CAD to MCNP UM geometry hexahedral mesh elements were specified along with sizes for the mesh elements. Trelis was selected as it is able to generate fully hexahedral meshes via python commands and export meshes in the ABAQUS file format which are compatible with MCNP. The resulting mesh can be seen in Fig. 3. A combined mesh containing all of the different materials was assembled in ABAQUS format which is supported by MCNP 6.1 UM simulations.

A Boolean subtraction of the parametrically produced CAD geometry and the bounding box was performed to allow space for the UM geometry to fit into the model. The bounding box was then incorporated into the CAD geometry so that the CAD geometry contained lithium ceramic layers, neutron multiplier layers, cooling plates and the UM bounding box. This geometry was then deconstructed and converted to CSG using McCad. Materials were once again automatically assigned. The meshed slice geometry was then inserted into the bounding box and UM tallies for heat deposition were added to the model.

The production of models, calculation of TBR, energy multiplication and volumetric heating was fully automated by using a combination of Python programmes and dedicated software.

A neutronics study was undertaken to demonstrate the use of the design tool. Two neutron multipliers were compared over a range of different blanket geometries. The height of the neutron multiplier and lithium ceramic were varied and the TBR and energy multiplication were calculated. Additionally the volumetric heating within a breeder blanket slice was calculated.

3. Results

The TBR values calculated for models with Be as the neutron multiplier were found to be significantly higher than models containing $Be_{12}Ti$ for all geometries simulated. While it is possible to achieve TBR values above 1.1 using $Be_{12}Ti$ and Li_4SiO_4 (at 60% enrichment) this would require large volumes of $Be_{12}Ti$ which would not be financially or environmentally desirable. Another option to increase the TBR for breeder blankets using $Be_{12}Ti$ multiplier would be to increase the ^{6}Li enrichment. This approach is also undesirable, as increasing the ^{6}Li enrichment is known to generate additional volumetric heating within the lithium ceramic bed; especially at the front side of the breeder zone near the first wall (Fig. 4).

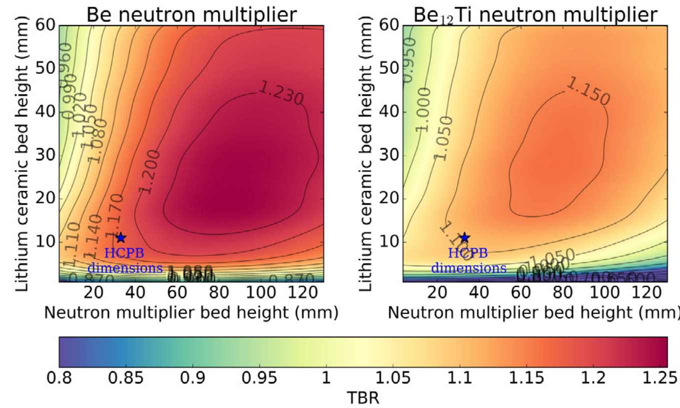

Fig. 4. TBR values for DEMO models with $Be_{12}Ti$ and Be neutron multipliers. HCPB design dimensions from [9].

The energy multiplication was found to be marginally higher for DEMO models using $Be_{12}Ti$ as the neutron multiplier compared to Be. Energy multiplication is directly related to the quantity of thermal energy produced, the amount of electricity generated and the profitability of fusion power plants. Additional electricity generation may therefore offset the high costs associated with the requirement for larger volumes of $Be_{12}Ti$. The blanket designs with the highest energy multiplication resulted in unacceptably low TBR values (Fig. 5).

The volumetric heating produced within the lithium ceramic pebble bed was found to be higher for the DEMO model with Be as the neutron multiplier (see Fig. 6 and Table 1). This shows a potential for additional ^{6}Li enrichment for $Be_{12}Ti$ based blankets while remaining within the heating limits for the lithium pebble bed (Fig. 6).

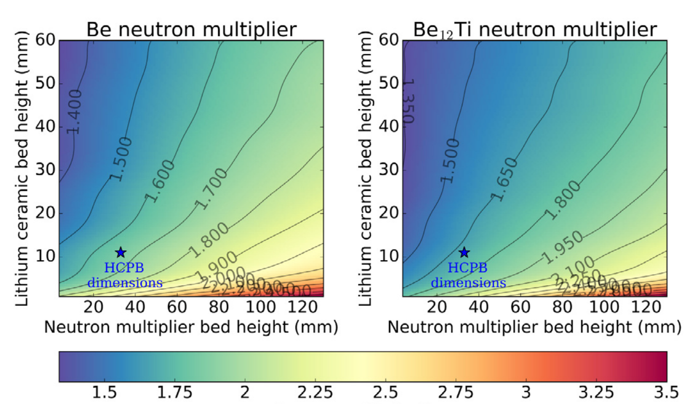

Fig. 5. Energy multiplication values for DEMO models with $Be_{12}Ti$ and Be neutron multipliers. HCPB design dimensions from [9].

Table 1
Volumetric heating for the different components in the blanket slice.

Component	Maximum volumetric heating ($W\,cm^{-3}$) Be	$Be_{12}Ti$
Lithium ceramic pebble bed	17.24	15.99
Neutron multiplier pebble bed	5.00	4.78
Eurofer first wall	5.90	5.94
Eurofer cooling plate	5.81	6.23
Tungsten armour	26.4	28.07

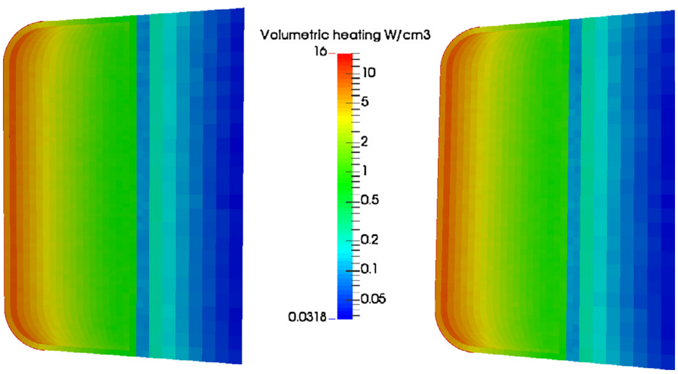

Fig. 6. Volumetric heating within the Li_4SiO_4 pebble bed for the model with $Be_{12}Ti$ (left) and Be (right). Slice shown has a neutron multiplier bed height of 32.4 mm and a lithium ceramic bed height of 11.6 mm.

4. Conclusion

This paper reports on creation of a neutronics evaluation tool and results from a demonstration neutronics study. The tool is capable of performing fast neutronic evaluations of a global MCNP model of the EU DEMO to assess the key neutronic performance figures of a blanket. Such fast evaluations are particularly valuable and allow designers to quickly arrive to optimised blanket geometries, dramatically reducing the pre-processing times and enabling a more integrated workflow through other engineering disciplines, mainly the blanket thermohydraulics and thermomechanics. In the future the code can potentially be coupled with a finite element codes, in order to be able to set up automatic goal optimisation routine through e.g. a genetic algorithm. MCNP was used for this demonstration study however other neutronics codes could also be used.

A parametric neutronics study was performed to assess a range of blanket geometries in terms of their TBR, energy multiplication and volumetric heating. Comparison of the two neutron multipliers over a range of geometries reveals that heterogeneous models using $Be_{12}Ti$ produce less tritium than Be. This is due to parasitic neutron capture within Ti and reduced neutron multiplication.

The $Be_{12}Ti$ neutron multiplier simulations also show lower volumetric heating in the lithium ceramic bed compared to the Be neutron multiplier simulations with the same geometry. This lower heat deposition could permit additional ^6Li enrichment; which would have the effect of increasing the tritium production. Additional interfaces to the tool are needed to ascertain the amount of ^6Li enrichment that can be tolerated and the resulting temperature of the components. Fortunately the neutronics design tool is based on CAD geometry which is compatible with future engineering simulations.

Acknowledgements

J. Shimwell would like to acknowledge the financial support of EUROfusion and EPSRC. 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. This work has also been part-funded by the RCUK Energy Programme [grant number EP/I501045] and the Institute of Physics Nuclear Industry Group. The authors would like to thank H. Gale, L. Pasuljevic and the FDS team for their help.

References

[1] H. Kawamura, et al., Development of advanced blanket materials for a solid breeder blanket of a fusion reactor, Nucl. Fusion 43 (2003).
[2] L. Evans, L. Margetts, V. Casalegno, L. Lever, J. Bushell, T. Lowe, A. Wallwork, P. Young, A. Lindemann, M. Schmidt, P. Mummery, Transient thermal finite element analysis of cfc-cu {ITER} monoblock using X-ray tomography data, Fusion Eng. Des. 100 (2015) 100–111.
[3] J. Goorley, et al., Initial MCNP 6 Release Overview – MCNP 6 Version 1.0, 2013.
[4] Y. Qui, et al., A generic data translation scheme for the coupling of high-fidelity fusion neutronics and CFD calculations, Fusion Eng. Des. 89 (2014) 1330–1335.
[5] L. Lu, et al., Improved algorithms and advanced features of the CAD to MC conversion tool McCad, Fusion Eng. Des. 89 (2014) 1885–1888.
[6] P. Pereslavtsev, Generic neutronic analyses for DEMO including the development of a global MCNP model EFDA D 2MJQ6K, 2015.
[7] A. Ribes, C. Caremoli, Salomé platform component model for numerical simulation, in: COMPSAC 07: Proceeding of the 31st Annual International Computer Software and Applications Conference, 2007, pp. 553–564.
[8] Trelis 16.1 csimsoft, trelis overview, 2016.
[9] F.A. Hernández, et al., HCPB Design Report Report, IDM Reference No. EFDA D 2MNBH9, Version 1.2, 2015.