UKAEA-CCFE-CP(20)75

Z. Vizvary, W. Arter, T. R. Barrett, D. Calleja, M. Firdaouss, J. Gerardin, M. Kovari, F. Maviglia, L. Richiusa

DEMO First Wall misalignment study

DEMO First Wall misalignment study

Z. Vizvary, W. Arter, T. R. Barrett, D. Calleja, M. Firdaouss, J. Gerardin, M. Kovari, F. Maviglia, L. Richiusa

This paper has been submitted to
30th Symposium on Fusion Technology (SOFT), Giardini Naxos, Messina, Sicily, 16-21 September 2018

DEMO First Wall misalignment study

Z. Vizvary[1*], W. Arter[1], T. R. Barrett[1], D. Calleja[3], M. Firdaouss[2], J. Gerardin[2], M. Kovari[1], F. Maviglia[4], M. L. Richiusa[1]

[1] CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2] IRFM CEA Cadarache, 13108, Saint Paul lez Durance, France
[3] University of Liverpool, Liverpool, UK
[4] EUROfusion – Programme Management Unit, Boltzmannstrasse 2, 85748 Garching, Germany

Within the DEMO first wall 3D shape design activity studying the effect of misalignment has started in 2017. Such assessments have been conducted in the past for ITER and penalty factor maps have been created [1]; this route could be feasible approach in the case of DEMO as well.

This paper details the tests and the methodology that allows assessing the effects of misalignments for DEMO. The test cases focus on the steady-state plasma operation (start of flat top). The aim is to understand the effect of basic misaligned cases, for example, radial protrusion/recession or poloidal rotation of a single module. To do so particle tracing software codes such as SMARDDA and PFCflux have been used to create heat flux maps that reaches the first wall surfaces. The obtained heat flux maps combined with the specified radiative heat load are used as input for simplified FE models of the blanket modules. As a result, not only the effect on heat flux, but also on the temperature (and later stress) distribution can be estimated.

The paper describes how the obtained results can be implemented in ANSYS in the identified critical cases from the test matrix that has been studied. The results obtained from the nominal heat flux map are compared to the misaligned cases. The peak temperature mitigating effect of 3D heat conduction is discussed.

This work paves the way to assess more realistic combined misaligned cases (such as misalignment from different thermal expansion, or due to electromagnetic loads etc. of neighbouring blankets) in the future.

Keywords: DEMO, First Wall, misalignment, particle heat flux, FEM

1. Introduction

The first wall (FW) alignment will deviate from ideal due to design features, manufacturing, assembly errors magnetic field deviations, thermal expansion difference due to non-uniform (or non-ideal) operational and accidental temperature distributions. The result of the deviation in alignment will most likely be elevated heat flux on the module surfaces, hot spots on exposed edges and a consequence of this elevated temperatures and mechanical stresses in the modules.

The heat load on the wall arises from two major components: radiative heat load, which is mostly uniform on the surface and charged particle heat load where the shape and magnitude of the heat flux on the surface is determined by the plasma configuration (the magnetic field lines), the tile shapes and shadowing. The charged particle heat load can be affected by the misalignment of the FW while the radiative component is unchanged. Studies are under way to understand the peak heat flux sensitivity to misalignments [2-4].

As the charged particle heat flux is non-uniform and usually the peak heat flux is limited to hot spots or other limited areas therefore considering 3D heat transfer can help to understand the effect on the peak temperatures and stresses in the FW and thus limits of allowable misalignments.

The assessment strategy will require bringing together information from several sources, most importantly heat flux maps on the plasma facing side and wall heat transfer coefficients in the cooling channels. The proposed methodology can be used to assess a component whether misaligned or not. There is more work to be done to make the method complete, also the presented heat load maps from misaligned modules are the results of the first set of cases.

2. Assessment strategy

The thermal (and later on structural) analysis can be carried out in a commercial FE package (i.e.: ANSYS). Input parameters need to be provided, however.

The heat flux map due to the charged particles are calculated by particle tracing software (SMARDDA/PFCFlux) and need to be imported into the FE code. This typically involves some form of interpolation as the FE mesh is usually different from that of the particle tracing software. Both particle tracing codes use legacy vtk file format (ASCII) as an output.

Modelling the cooling in detail in FE is possible, however it can be resource extensive, hence instead of actual fluid dynamic analysis it can be sufficient to impose wall heat transfer coefficients on the cooling channel locations. These wall heat transfer coefficients (WHTCs) can be available from different sources, CFD analysis, using in-house thermal-hydraulic codes, analytically developed formulae, or measurement [5-6]. In this paper a constant value and constant bulk fluid temperature (300 °C He) has been used, but later a table using well known formulae or results from other analysis will be implemented. Just as

author's email: zsolt.vizvary@ukaea.uk

with the heat flux maps the fluid temperature dependent WHTC maps could also be interpolated onto the FE mesh.

Simplification of the 3D geometry in the FE model is desired due to the large number of misaligned cases. Shell elements will be used in this work, but the methodology is the same as for more detailed solid models as well, and will be done for validation, once the study has been concluded. A shell element-based FE model is proposed to allow fast assessment of various misaligned cases for any given modules. While this is a great way to reduce the number of nodes and elements, of course the geometric detail of the model, thus will reduce. Most important feature may be the model of the cooling channels. Alternating cooled and uncooled bands can be defined to model them. Layered thermal shell element will be used (ANSYS: SHELL132) thus results will be available through the thickness in the required number of points. This also allows us to incorporate tungsten (armour) properties in the plasma facing layer without adding further details to the model.

ANSYS workbench has means to import data easily from other codes, however the above layered shell element is not available and not easy to utilise. At the same time, importing the loads in APDL is a bigger challenge, the number of points in the source and target may be limiting, in fact it does seem like that one blanket module with a fine mesh is already over the limit.

One way to overcome this problem is to partition the target geometry and interpolate the source data in several steps. Other solution can be interpolating outside the FE, an in-house python code has been developed, albeit this process is more time consuming.

Post-processing is carried out within ANSYS APDL, however later the results may be written to vtk files as well. This would allow common platform with SMARDDA and PFCFlux.

3. Heat flux penalty factors

The basis of this work is the 2017 DEMO baseline model with multi-module segments (MMS) [7]. A set of rigid-body displacements of FW modules have been specified in order to analyse the sensitivity of thermal charged particle loads to module misalignments. A test matrix has been setup, and initially 24 cases were checked, all of them at normal operational condition (start of flat top, SOF). The full test matrix has been analysed by PFCFlux and partial results are available by SMARDDA.

Starting from the baseline design positions, misalignments of FW modules can be described by a combination of three translations and three rotations. As the first step in the modelling it would be beneficial to understand the effects of this individual deviations even if they are not particularly linked to a manufacturing, assembly or other error. Important to note that although the modules are individually misaligned the toroidal symmetry has been kept. In the future the effect on a single protruding component should be investigated as well, even though the shadowing provided by the misaligned modules to each other is thought to be negligible.

Based on the test results of PFCFlux and SMARDDA heat flux penalty factor maps can be produced. An example is shown for module 7 and 8 (Table 1).

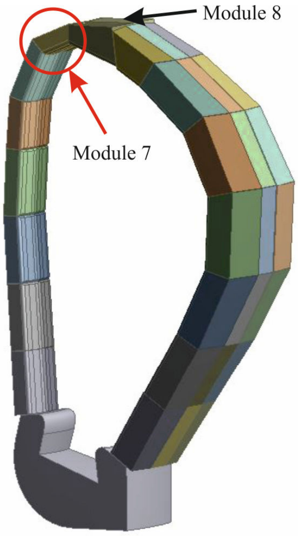

Figure.1. Module 7 location on the inboard blanket segment.

Table 1: Peak heat flux for surface normal translation (radial step) with PFCFlux

Radial misalignment of individual modules and peak heat flux [MW/m^2] for respective modules					
Module	-10 mm	2 mm	5 mm	10 mm	20 mm
7	0.59	0.67	0.67	0.68	0.99
8	0.2	-	-	0.42	0.43

Table 2: Penalty factors for surface normal translation (radial step) with PFCFlux

Radial misalignment of individual modules and penalty factors for respective modules					
Module	-10 mm	2 mm	5 mm	10 mm	20 mm
7	0.89	1.02	1.02	1.03	1.50
8	0.59	-	-	1.24	1.26

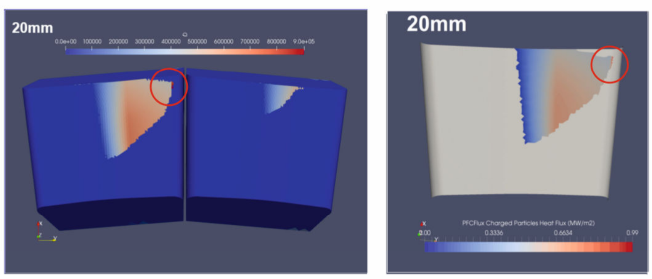

Figure 2: SMARDDA and PFCflux heat flux maps for module 7 with 20 mm normal translation (SOF)

The paper is focused on one of the critical modules: module 7 (Figure 1). Being close to the secondary null where the field lines are opening this module is thought to be one of the most sensitive to any misalignment. The particle tracing results has showed one of the critical cases is the normal (to surface) translation by 20 mm. There is a new peak heat flux location appearing close to the side of the module (Figure 2).

4. Thermal analysis

After the heat flux maps have been produced they have been applied to the shell based thermal model.

As explained above there are serious advantages of using a shell-based model, however the loss of details is a drawback and the model might need further fine tuning.

A reference case has been chosen [8]. The parameters of module 7 have been adjusted to be similar to those described in [8]: FW thickness 3.5 mm; 15 mm wide channels with 5 mm ribs in between; the channel heat transfer coefficient is also the same 6000 W/m^2 uniform with bulk fluid temperature 300 °C, and the heat load applied is 500 kW/m^2. However, no volumetric heat load has been considered.

The results of this reference case are fairly close to those obtained in [8]. Maximum temperature in the Eurofer 97 is 506 °C, while in [8]it is ~540 °C (excluding the peaks at the edges). Considering the simplifications and potential differences in the load application it is a good starting point.

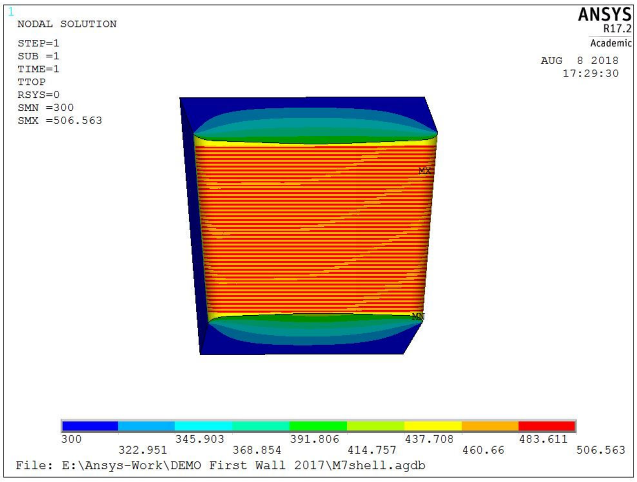

Figure 3: Reference solution

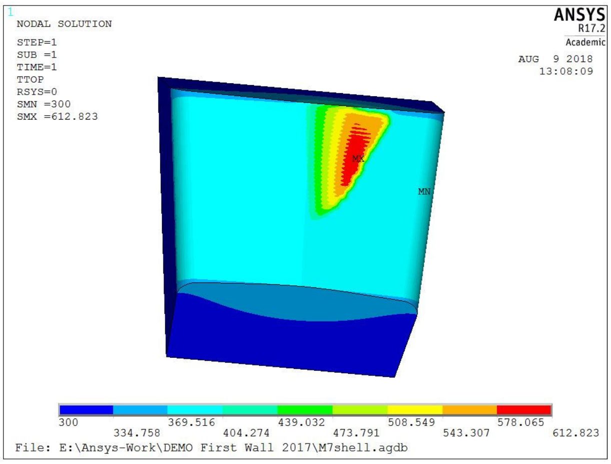

Figure 4: ANSYS result: Temperature distribution [°C] on module 7 surface (nominal case).

Next, changes have been made to the model to reflect the recent HCPB design, where the Eurofer thickness is 3 mm and the FW also has a 2 mm tungsten armour on it. The worst case radiative heat flux [9] is 0.22 MW/m^2. The peak temperature in this case is 381 °C.

Then the charged particle heat flux is applied (SOF) with a peak heat flux of 0.66 MW/m^2 (nominal case). The maximum temperature in this case is 613 °C in the tungsten, in the Eurofer it is 602 °C. This is slightly above the maximum operating temperature of Eurofer (550 °C).

Comparing to the 20 mm displaced (protruded) case the peak charged particle heat flux increases to 0.99 MW/m^2, and it is a hot spot like shape located on the upper right-hand side corner of the module (Figure 2 and 5) rather than in the middle. The temperature distribution however shows that the peak temperature is not occurring at this location, but still rather in the middle. The maximum temperature on the surface increases by 629 °C (618 °C in Eurofer) as a result of the 20 mm misalignment (Figure 6).

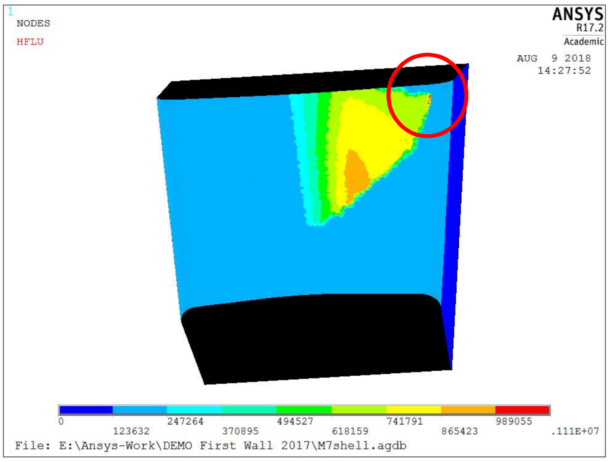

Figure 5: Imported heat flux on the ANSYS model (see Figure 2 to compare).

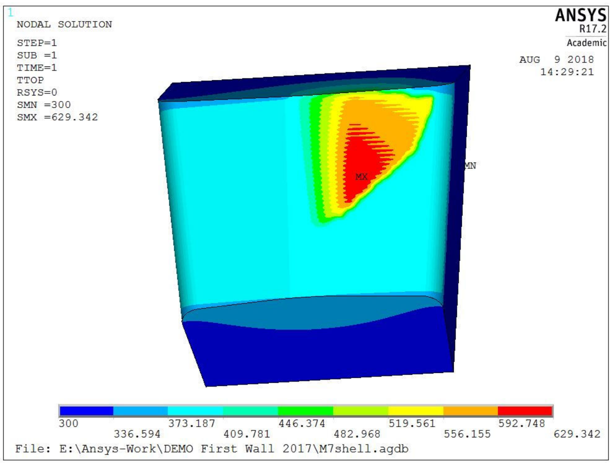

Figure 6: ANSYS result: Temperature distribution [°C] on module 7 surface (nominal case).

The peak heat flux value of the ANSYS model is slightly lower than expected it is likely to be the result of the interpolation.

5. Summary

The paper has described a methodology that allows the assessment of misalignments with regards to the temperature in the tile. The shell element-based FE model allows relatively quick assessment of cases. However, this model still has to be refined and adjusted to more detailed models, so that the obtained temperature results are accurate and reliable. Further critical cases need to be run.

So far, the worst case seems to be the surface normal translation of module 7 by 20 mm resulting in a penalty factor of 1.5 and consequent hotspot of 0.99 MW/m^2 heat flux.

The FE analysis showed that in the misaligned case the peak temperature is not at the peak heat flux location. The reason for this is that the peak heat flux is a hot spot at the edge of the charged particle heat flux map and heat transfer to the colder regions helps to keep the temperature down.

Charged particle heat flux maps for an initial test matrix have been calculated using SOF, but more load cases (end of flat top (EOF), start up/ramp down, VDE etc.) need to be considered. Also, more realistic deviations need to be assessed, where a full segment, either multi-module (MMS) or single-module (SMS) is considered. Individual module like translations to SMS cannot be applied. Displacements from other analysis [10] could be imposed on the mesh to obtain the heat flux maps.

In this work constant values of WHTCs and bulk coolant temperatures have been used, so that comparison with previous work is possible. However more sophisticated WHTCs need to be applied to the model. There are advanced cooling channel designs [11] to improve the heat removal and keep the Eurofer temperature in the operating window.

It has to be noted that with discrete plasma facing components that are not toroidal continuous it has been seen that both PFCflux and SMARDDA are struggling with power balance. The reasons are being explored, they thought to be part of algorithmic and physics related. Particle tracing software typically deploy backward tracing, if a protruding component is present, there are regions of the midplane that are not mapped to the wall resulting in a power balance difference.

It is assumed that the charged particles follow the magnetic field lines. Recent studies [12] indicate that this assumption may not be true, a non-parallel heat flux component seems to exist. This physics will have to be understood and then incorporated in particle tracing software to obtain more accurate and reliable results.

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. To obtain further information on the data and models underlying this paper please contact publicationsmanager@ccfe.ac.uk.

References

[1] R.Mitteau, P.Stangeby, H.Labidi, R.Bruno, R.Raffray: The combined effects of magnetic asymmetry, assembly and manufacturing tolerances on the plasma heat load to the ITER first wall, Journal of Nuclear Materials 463 (2015) 411–414

[2] F. Maviglia, G. Federici, R. Wenninger, R. Albanese, R. Ambrosino, C. Bachmann, L. Barbato, F. Cismondi, M. Firdaouss, V.P. Loschiavo, C. Lowry: Effect of engineering constraints on charged particle wall heat loads in DEMO, Fusion Engineering and Design 124 (2017) 385–390

[3] D. C. Calleja, W. Arter, M. De-Angelis, E. Patelli: Strategy for Sensitivity Analysis of DEMO first wall, Proceedings of the joint ICVRAM ISUMA UNCERTAINTIES conference, Florianopolis, SC, Brazil, April 8-11, 2018

[4] Yu. Igitkhanov, R. Fetzer, B. Bazylev: Effect of design geometry of the demo first wall on the plasma heat load, Nuclear Materials and Energy 9 (2016) 560–564

[5] M. Ilic, G. Messemer, K. Zinn, R. Meyder, S. Kecskes, B. Kiss: Experimental and numerical investigations of heat transfer in the firstwall of Helium-Cooled-Pebble-Bed Test Blanket Module – Part 1: Presentation of test section and 3D CFD model, Fusion Engineering and Design 90 (2015) 29–36

[6] M. Ilic, G. Messemer, K. Zinn, R. Meyder, S. Kecskes, B. Kiss: Experimental and numerical investigations of heat transfer in the firstwall of Helium-Cooled-Pebble-Bed Test Blanket Module – Part 2: Presentation of results, Fusion Engineering and Design 90 (2015) 37–46

[7] First wall design in 3D v2.2: https://idm.euro-fusion.org/?uid=2MJGX9

[8] F. Cismondi, S. Kecskés, M. Ilic, G. Légrádi, B. Kiss, O. Bitz, B. Dolensky, H. Neuberger, L.V. Boccaccini, T. Ihli: Design update, thermal and fluid dynamic analyses of the EU-HCPB TBM in vertical arrangement, Fusion Engineering and Design 84 (2009) 607–612

[9] DEMO PFC Heat Load Specifications_v0.3: https://idm.euro-fusion.org/?uid=2NFPNU

[10] Z. Vizvary, D. Iglesias, D. Cooper, R. Crowe, V. Riccardo: Progress on DEMO blanket attachment concept with keys and pins, Fusion Engineering and Design 98–99 (2015) 1674–1677

[11] F. Arbeiter, C. Bachmann, Y. Chena, M.Ilic, F. Schwab, B. Sieglin, R. Wenninger: Thermal-hydraulics of helium cooled First Wall channels and scopinginvestigations on performance improvement by application of ribsand mixing devices, Fusion Engineering and Design 109–111 (2016) 1123–1129

[12] D. Iglesias, P. Bunting, J. W. Coenen,, G. Matthews, R. A. Pitts, S. A. Silburn, I. Balboa, I. Coffey, Y. Corre, R. Dejarnac, J. Gaspar, E. Gauthier, S. Jachmich, K. Krieger, S. Pamela, V. Riccardo. M. F. Stamp: An improved model for the accurate calculation of parallel heat fluxes at the JET bulk tungsten outer divertor, 2018 Nucl. Fusion in press https://doi.org/10.1088/1741-4326/aad83e