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DEMO First Wall misalignment study

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ABSTRACT

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

This paper details the methodology that allows the effects of misalignments to be assessed for DEMO. The test cases focus on 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 reach the first wall surfaces. These 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) distributions 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 mitigating effect of the 3D nature of the heat conduction on the peak temperature is discussed.

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

1. Introduction

The first wall (FW) alignment will deviate from ideal due to design features, manufacturing non-conformances, assembly errors, magnetic field deviations and 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 [1], hot spots on exposed edges and, as 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 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, heat transfer in the lateral directions can help to limit the effect on the peak temperatures and stresses in the FW and thus influences allowable misalignments.

The assessment 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, the presented work is based on the first set of misaligned cases.

2. Heat flux penalty factors

The basis of this work is the 2017 DEMO baseline model with multi-

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module segments (MMS) [5]. A set of rigid-body displacements of FW modules has been specified in order to analyse the sensitivity of thermal charged particle loads to module misalignments. A test matrix has been set up, and initially 24 cases were checked, all of them at normal operational conditions (start of flat top, SOF). The full test matrix has been analysed by both PFCFlux and SMARDDA [6].

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 these individual deviations even if they are not particularly linked to a manufacturing, assembly or other error.

It is important to note that, although the modules are individually misaligned, the toroidal symmetry of the DEMO sectors has been kept: misalignment of an individual module is the same in every vacuum vessel sector. It is assumed that the toroidal distance is long enough that the modules provide only negligible shadowing to the respective modules in the neighbouring sector. However this will have to be confirmed by investigating single protrusion of modules.

The outcome of these 24 cases in the test matrix was a set of heat flux maps from which heat flux penalty factors were calculated. The heat flux penalty factor (f) is defined as the ratio of the peak heat flux value at the misaligned position (Q_{mis}) divided by the peak heat flux at the nominal position (Q_n) for the charged particle load (1).

$$f = \frac{Q_{mis}}{Q_n} \tag{1}$$

Surface normal translations of modules 7 and 8 towards the plasma (Fig. 1) have been identified as the worst cases; the modules are close to the secondary null where the field lines are opening. Moving one module 7 by 20 mm inwards results in a new peak heat flux location close to the side of the module (Fig. 2).

Peak heat flux values and penalty factors for modules 7 and 8 are shown in Tables 1 and 2.

3. Thermal analysis

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

The heat flux map due to the charged particles is calculated by particle tracing software (SMARDDA/PFCFlux) and needs 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 intensive. 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 [7,8]. 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 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 the latter 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 will be reduced. The most important feature may be the model of the cooling channels. Alternating cooled and uncooled bands have been defined to model them. Layered thermal shell element have been used (ANSYS: SHELL132) and thus results are available through the thickness at 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.

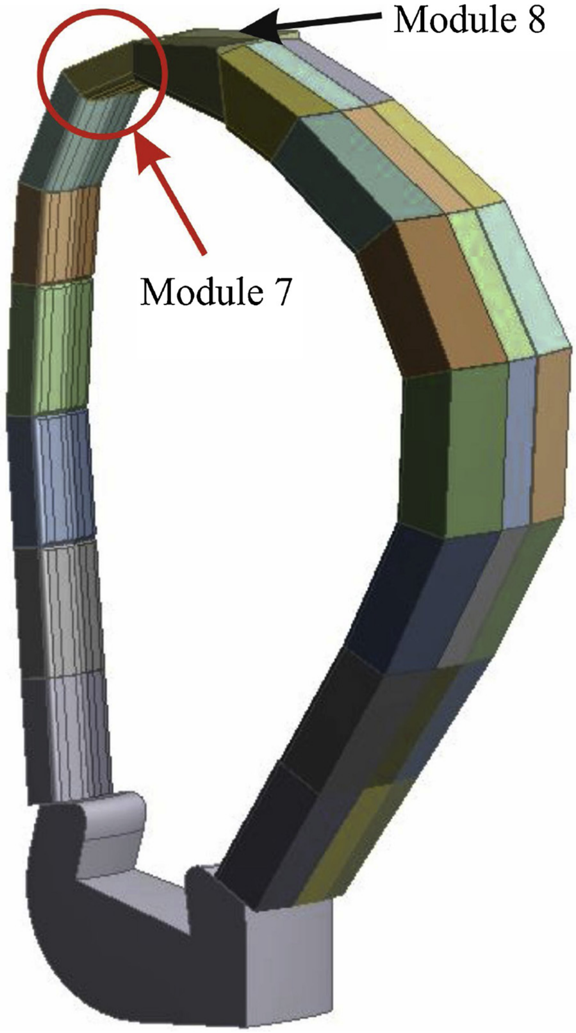

Fig. 1. Module 7 location on the inboard blanket segment.

ANSYS Workbench has the ability to import data easily from other codes, but 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 a single 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. Another solution is to interpolate outside the FE, for which an in-house python code has been developed. However, this process is more time consuming.

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

A reference case has been chosen from [9]. The parameters of module 7 have been adjusted to be similar to those described in [9]: 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 [9]. Maximum temperature in the Eurofer 97 is 506 °C (Fig. 3), while in

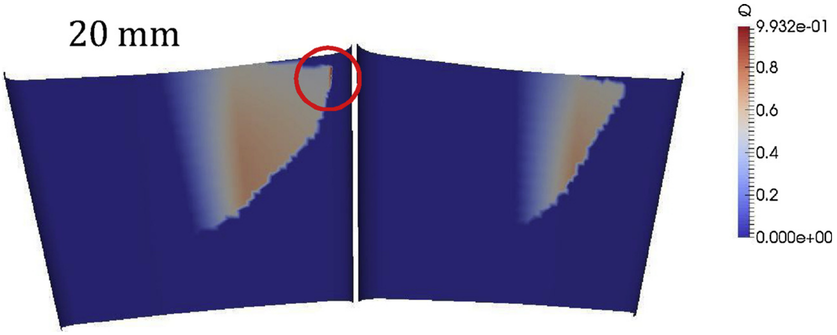

Fig. 2. SMARDDA heat flux maps for two module 7, one with 20 mm normal translation (SOF) [MW/m^2].

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

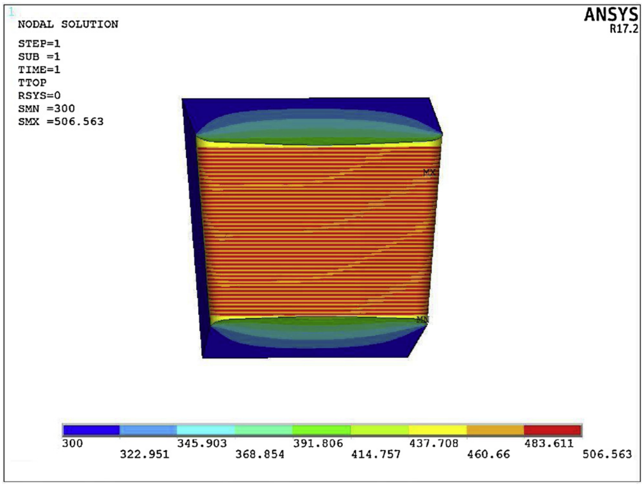

Fig. 3. Reference solution.

[9] 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.

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 [10] is 0.22 MW/m^2. The peak temperature in this case is 381 °C.

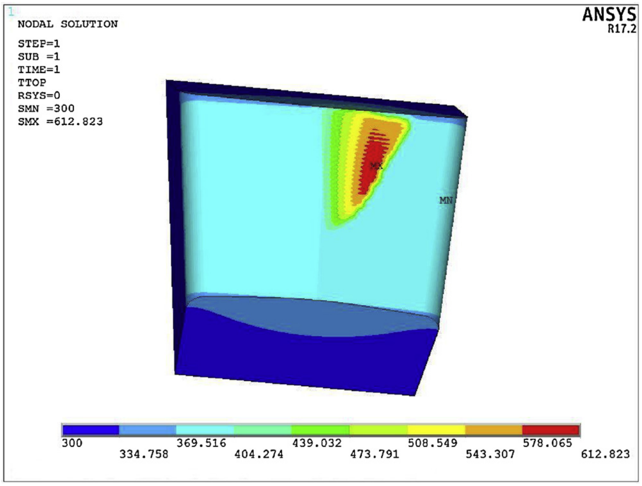

Fig. 4. ANSYS result: Temperature distribution [°C] on module 7 surface (nominal case).

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 (Fig. 4), in the Eurofer it is 602 °C. This is slightly above the maximum operating temperature of Eurofer (550 °C).

Compared 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 (Figs. 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 to 629 °C (618 °C in Eurofer) as a result of the 20 mm misalignment (Fig. 6).

The peak heat flux value of the ANSYS model is slightly lower than

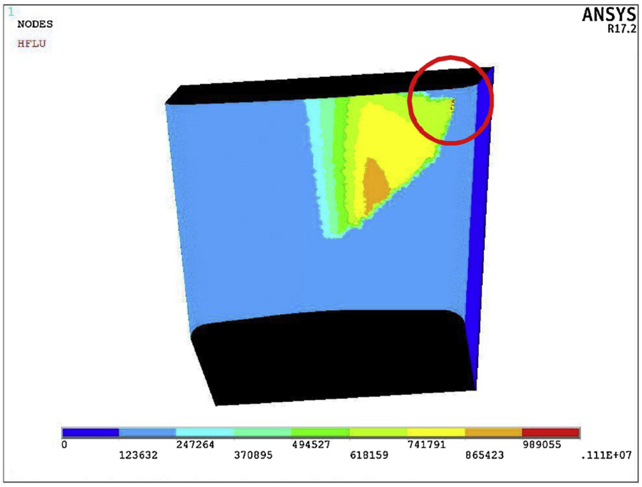

Fig. 5. Imported heat flux on the ANSYS model (see Fig. 2 to compare).

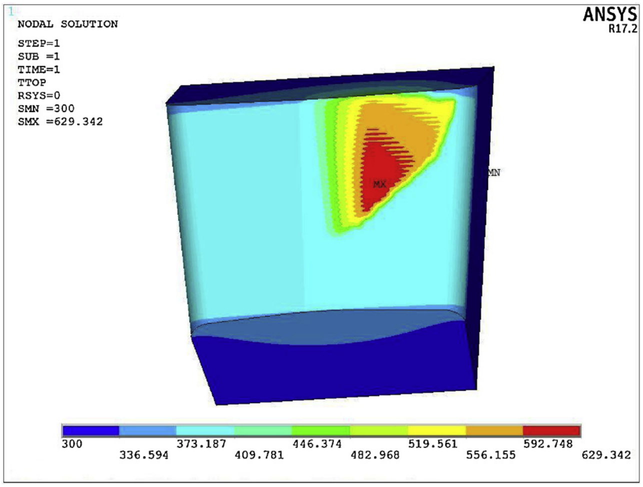

Fig. 6. ANSYS result: Temperature distribution [°C] on module 7 surface (nominal case).

expected, which is likely to be a result of the interpolation.

4. Summary

A method that allows the assessment of misalignments with regard to the temperature in the module has been described. 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 hotspot due to charged particles.

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.

The 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 [11] could be imposed on the mesh to obtain the heat flux maps.

Constant values of WHTCs and bulk coolant temperatures have been used, so that comparison with previous work is possible. However, more sophisticated WHTCs could be applied to the model. There are advanced cooling channel designs [12] 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 toroidally continuous, it has been seen that both PFCflux and SMARDDA are struggling with power balance. The reasons are being explored, they are thought to be part algorithmic and part physics related. Particle tracing software typically deploys 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 [13] 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.

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