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Thermo-mechanical analysis of Wendelstein 7-X plasma facing components

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HIGHLIGHTS

- Thermo-mechanical analysis of HHF divertor module TM-H09 shows that it can withstand heat loads of 10 MW/m^2 in steady state when the supports were optimized accordingly.
- FE calculations indicate that the tiles of baffles and heat shields can withstand stationary heat loads of 250 kW/m^2, but that the pulse length of plasma operation must be limited depending on the number of full load (500 kW/m^2) cycles.
- Gap requirements for wall panels during assembly were defined based on several FE calculations.

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ABSTRACT

The stellarator experiment Wendelstein 7-X (W7-X) is designed for stationary plasma operation (30 min). Plasma facing components (PFCs) such as the divertor targets, baffles, heat shields and wall panels are being installed in the plasma vessel (PV) in order to protect it and other in-vessel components. The different PFCs will be exposed to different magnitude of heat loads in the range of 100 kW/m^2–10 MW/m^2 during plasma operation. An important issue concerning the design of these PFCs is the thermo-mechanical analysis to verify their suitability for the specified operation phases. A series of finite element (FE) simulations has been performed to achieve this goal. Previous studies focused on the test divertor unit (TDU) and high heat flux (HHF) target elements. The paper presents detailed FE thermo-mechanical analyses of a prototype HHF target module, baffles, heat shields and wall panels, as well as benchmarking against tests.

1. Introduction

The stellarator experiment W7-X being constructed in Greifswald, Germany, is designed for stationary plasma operation (30 min) with steady state heating of up to 10 MW ECRH and 10 s pulse heating power of up to 20 MW with additional NBI and ICRH [1]. The PFCs [2,3] as shown in Fig. 1 comprise the divertor targets (shown in magenta), baffles (brown), heat shields (blue), wall panels (cyan) and minor others (gray). They are being installed in the PV in order to protect it and other in-vessel components behind them from the convectional/radiative heat coming from the plasma. All these PFCs need to be actively water cooled during stationary operation. However, in view of the technical challenges of the HHF divertor targets, it was decided for the first phase of operation to use the simpler inertially and radiatively cooled TDU and to limit the operation to short plasma pulses [4,5]. Except for the divertor targets, all the other PFCs will be installed at the beginning as designed for stationary operation and connected to the internal water cooling circuit but not cooled unless required. After about two years of operation, the TDUs will be replaced by the HHF divertor targets.

The design of the PFCs needs to be checked by thermo-mechanical analysis in order to verify their suitability for the specified operation phases. A series of FE simulations has been performed to achieve this goal. Previous studies focused on the TDU and HHF target elements (TEs) as presented in [5]. This paper concentrates on recent results and issues of thermo-mechanical studies on the PFCs for stationary operation.

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Table 1
Heat loads on PFCs during stationary operation phase.

PFCs	Type of load	Average heat load, kW/m^2	Local peak heat load	
			Value, kW/m^2	Spatial extension, cm
HHF divertor	Convection	3000	10,000	(8–15)[a] × 150[b]
Baffles	Radiation	250	500	10[a] × 150[b]
Heat shields	Radiation with some convection	250	500	10[a] × 100[b]
Wall panels	Radiation	100	200[c]	20[a] × (300–400)[b]

[a] Poloidal extension.
[b] Toroidal extension.
[c] This heat load is 10 s pulse, the others are continuous.

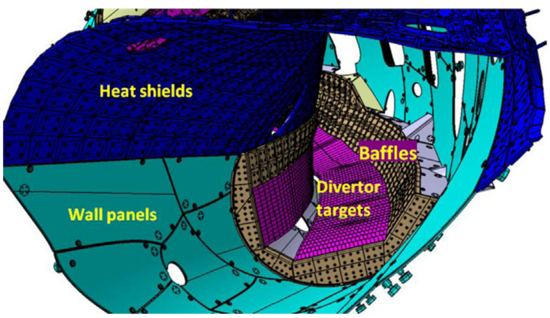

Fig. 1. PFCs, toroidal view at triangle cross-section.

During stationary operation, the different PFCs will receive heat loads of different types (convection and/or radiation) and magnitudes due to their different positions [6,7] relative to the plasma, as shown in Table 1. Detailed thermo-mechanical analyses of the PFCs under these heat loads are presented in following sections.

2. HHF divertor targets

The HHF divertor system consists of ten divertor units, two per each of the five symmetric modules of the machine. Each divertor unit has ten target modules. Each module is composed of 8–12 TEs and in total there are 890 TEs for the whole divertor system [8]. A prototype was developed for the horizontal HHF target module 09 (TM-H09), see Fig. 2, with twelve TEs. Each TE is 250 mm long and 55 mm wide and has ten ~7 mm thick CFC tiles bonded onto the CuCrZr heat sinks (3 mm interlayer) [9]. These TEs are bolted to two stainless steel (SS) support rails which are attached to the PV. The twelve TEs are actively water cooled and arranged in six parallel circuits, two by two in series with three pipes for the connection between themselves and the manifolds. The manifolds are connected to the main in-vessel pipe work at one side (not shown in Fig. 2). At the other side they are supported by a SS frame and a stiff beam which in turn are attached to the two support rails. Nickel (Ni) adapters are used between the SS pipes and the CuCrZr heat sinks in order to obtain reliable joints. The TEs are fully fixed to the support rail at the side where they are connected to the cooling pipes, while at the other side they can slide radially relative to the other support rail. One of the two sides of the manifolds can move toroidally relative to the manifold supports. The stiff beam can slide radially relative to the support rail.

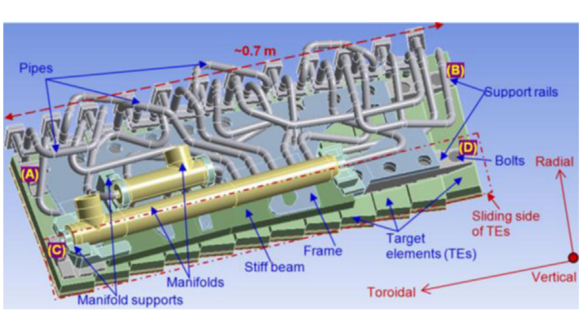

Fig. 2. Global FE model of HHF divertor TM-H09, view from the plasma vessel side.

A 3D global FE model as shown in Fig. 2 was created for TM-H09 to perform thermo-mechanical analyses with the main purpose to estimate deflections, thermal stresses and requirements for module attachment. The temperature dependent material properties of CFC, interlayer, CuCrZr and SS, and the orthotropic thermal conductivity and thermal expansion coefficients for CFC were used. Table 2 shows the temperature dependent properties of the materials.

The thermal loads and boundary conditions (BCs) were (a) heat flux of 10 MW/m^2 applied onto the top surfaces of the central four CFC tiles of each TE; (b) heat transfer coefficient from the cooling wall of the heat sink to the cooling water [10] which is dependent on the average film temperature at constant cooling water temperature of 60 °C; and (c) radiation from the heated top surfaces of the CFC tiles to ambient (200 °C).

The thermo-mechanical loads were the body temperature distribution from thermal calculation and 2.5 MPa water pressure. The mechanical BCs were applied to the end areas (marked as (A), (B), (C) and (D) in Fig. 2) of the two support rails. Two different mechanical load cases were investigated: firstly, load case 1 where toroidal sliding in the fixation areas (B), (C) and (D), and radial sliding in the fixation areas (C) and (D) were allowed. Secondly, load case 2 where in addition all rotational degrees of freedom were released for the fixation areas (A), (B), (C) and (D).

The thermal calculation shows that the maximum temperatures of the CFC tiles, interlayers and CuCrZr heat sinks are 911 °C, 481 °C and 321 °C, respectively, which correspond to the experimental results [11]. The temperatures of the other components are lower than 70 °C.

In the elastic calculation of load case 1, von-Mises stresses in the support rails are higher than 1000 MPa in a large area, which is far beyond the limit of 525 MPa (secondary stress limit $3S_m$) for SS EN 1.4435 at 70 °C. After the release of the rotations in the fixation areas (load case 2), the stresses are reduced significantly. The maximum stress in one of the support rails is 409 MPa. The maximum stress in the other support rail is still high (820 MPa), but the stress higher than 525 MPa is observed only in a very small region. The support rail is not expected to be damaged because the level of stress will decrease as soon as some local plastic deformation occurs in this region. The maximum stresses in the cooling pipes, manifolds, manifold supports, stiff beam and frame are 209 MPa, 348 MPa, 279 MPa, 138 MPa and 314 MPa, respectively. The maximum stress in the Ni adapter is 65.8 MPa, which is acceptable. The stresses in the CFC tiles and CuCrZr heat sinks are lower than the thermal stress limits for the corresponding materials. The vertical displacements of the TM-H09 TEs are in the range of 0.48 mm upwards, and 1.1 mm downwards (Fig. 3), which can be compensated by adjustment. The maximum rotational displacement in the four fixation areas is about 0.2°.

Table 2
Temperature dependent properties of the materials.

Materials	Thermal conductivity, W/mK		Coefficient of thermal expansion
CFC	Radial	80 at 20 °C 40 at 1000 °C	2.1E − 6
	Toroidal	120 at 20 °C 60 at 1000 °C	1.0E − 6
	Vertical	325 at 20 °C 140 at 1000 °C	2.5E − 7
Interlayer		125 at 20 °C 190 at 600 °C	1.55E − 5 at 20 °C 2.0E − 5 at 600 °C
CuCrZr		318 at 20 °C 349 at 600 °C	1.67E − 5 at 20 °C 1.86E − 5 at 600 °C
SS EN 1.4435		14.3 at 20 °C 18.3 at 500 °C	1.53E − 5 at 20 °C 1.83E − 5 at 500 °C
Nickel		90	1.3E − 5

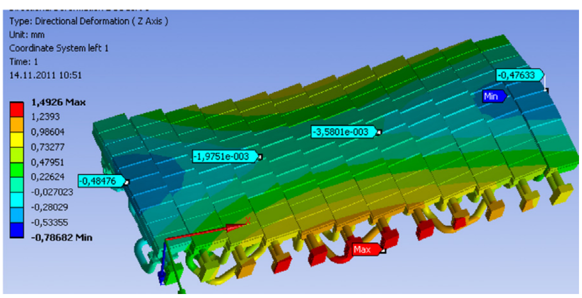

Fig. 3. Vertical displacement (mm) of TM-H09 (load case 2), view from the plasma side.

The results reveal that the TM-H09 can withstand heat loads of up to 10 MW/m^2 in steady state when the supports allow rotation and translation. The design of the supports was optimized accordingly. Two other types of HHF target modules with minor deviation of geometric parameters were studied too, using a simple model with only one TE. The investigation indicates that both modules do not have structural problems under heat loads of 10 MW/m^2.

3. Baffles and heat shields

The baffles and heat shields are modules [12] of a series of graphite tiles bolted to CuCrZr heat sinks which are brazed on ⌀12 mm × 1 mm common SS cooling pipes. A 1 mm layer of Sigraflex is squeezed between each tile and heat sink to improve the thermal contact (Fig. 4).

The baffle module is supported by a stiff support frame whereas the heat shield module is attached to the PV via more flexible supports. Fig. 5 shows a typical baffle module and heat shield module.

Both steady state and transient thermo-mechanical FE analyses of a tile (Fig. 4) were performed based on the heat loads listed in Table 1. The displacements at the end of the pipe were not constrained.

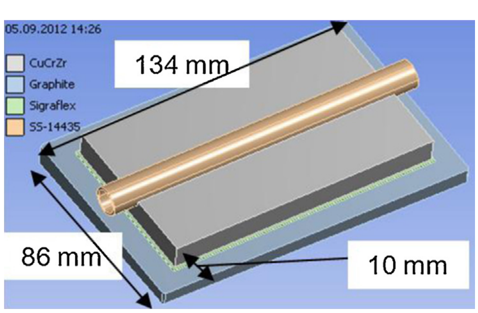

Fig. 4. Structure of a baffle and heat shield tile.

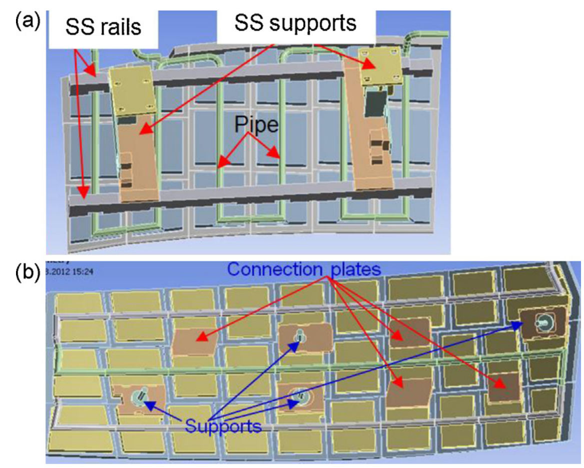

Fig. 5. Support structure of a typical baffle module (a) and heat shield module (b).

Two significant issues were found in the course of analyses: (1) the large temperature gradient in the pipe results in high stresses and (2) the cooled but still rather hot back surfaces of graphite tiles lead to heat loads on the PV significantly exceeding the design limit.

The results showed that the tile can withstand the average heat load for steady state operation, but that under local peak heat load it can only be operated in pulses of up to 45 s to limit the thermal stress in the cooling pipe.

The temperature gradient is mainly determined by A_q/A_{pipe}, the area ratio of heated area of graphite tile to the contact area between the cooling pipe and the heat sink. The most critical tiles are the outermost ones at the module edge. The relations A_q/A_{pipe} as well as A_q/A_{sigra} (which is the ratio of the tile to the heat sink areas) for the edge tiles are shown in Fig. 6. On the other hand, the edge

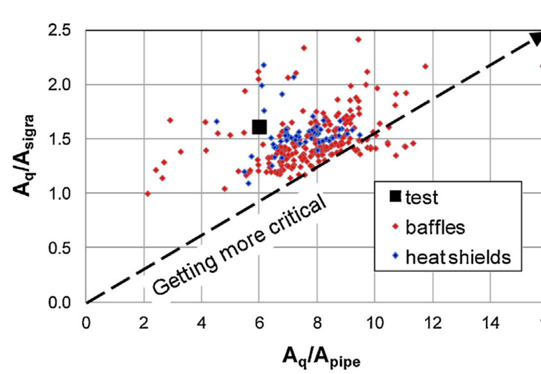

Fig. 6. Area ratios of heated area to cooled area and heated area to Sigraflex area for W7-X edge tiles and the tested tile.

tiles are less critical with respect to thermal deformation of the cooling pipe, which is less restrained in such tiles than in the tiles in the middle of the module. The support structure also affects the mechanical behavior of the tiles.

Taking all these factors into consideration, an FE model of one baffle module and an FE model of one heat shield module were created to study the overall thermo-mechanical response of these modules. The results of the calculations showed unacceptable thermal stress in the cooling pipe of the baffle module even under steady state loads of 250 kW/m^2 due to stiff restraint of the thermal deformation of the cooling pipe by the support structure. The flexible support structure of the heat shield module did not lead to significantly increased stresses.

However, a thermal test showed that the tile can survive 500 cycles of design load heating with pulse lengths of 200 s [3,13]. The tested tile showed almost the same relation as the FE calculated single tile, but this value was not conservative as compared to the edge tiles in W7-X (Fig. 6).

To clarify the mismatch between the test results and the elastic analysis results, elastic plastic analyses were carried out on a single tile using a temperature distribution that was successfully benchmarked against the test results [13]. The primary result is that the plastic strain in the cooling pipe under test conditions is within the low cycle fatigue limit for the tested 500 cycles. For W7-X, 60,000 plasma shots are expected. Assuming all of them to be full load cycles, the allowed pulse length of a local peak heat load would be 40 s which is coincidentally consistent with the result of FE elastic analysis of a single tile. In reality, most of the shots will not be full load cycles, i.e. the allowed full load pulse length can be much higher. The pulse lengths depending on heat loads and corresponding cycle numbers are currently being evaluated.

The temperature of the back surfaces of graphite tiles is heavily affected not only by the A_q/A_{pipe} ratio but also by the A_q/A_{sigra} ratio. Thermal calculation results indicate that the heat load on the PV coming from tiles is higher than the limit of 1.9 kW/m^2. A potential solution by installing a radiation shield at the backside of the tile clamped onto the cooling pipe is considered in [14].

4. Wall panels

A wall panel (WP) consists of two SS plates of 5 mm and 1.5 mm thickness which are laser welded together forming a cooling channel [6]. The structural reliability was validated by burst testing and transient heat flux testing [6]. An important issue is the definition of gaps required between WPs in order to avoid collisions and overload of the supports to the PV. Large expansion and deformation during baking and plasma operation due to heat loads, internal pressure, and PV deformation were considered. Three representative wall panels were selected for thermo-mechanical analyses, which were performed for two load cases. The normal plasma operation load case includes 100 kW/m^2 heat load, 5813 W/m^{2}K heat transfer coefficient in the cooling channel at constant cooling water temperature of 80 °C, and 2 MPa cooling water pressure. The baking load case considers 160 °C uniform temperature at the same water pressure. Fig. 7 shows the resulting deformation of the largest wall panel during normal operation. Directional displacements were extracted from FE calculations for every edge of the WPs in a local coordinate system. Based on this information, the gap requirements to be checked during assembly were defined in toroidal and poloidal directions separately, depending on the curvature of the WPs, the distances between all relevant support pairs of a series of WPs, and the available sliding space between the panels and their supports.

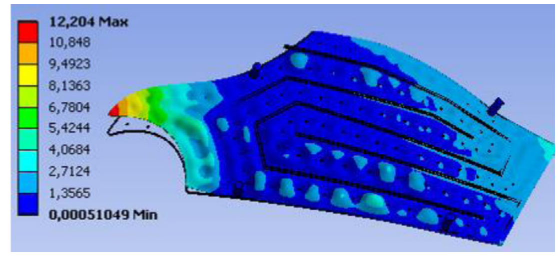

Fig. 7. Deformation (mm) of a wall panel during operation, view from the plasma vessel side.

5. Conclusion

A series of FE analyses has been performed to verify and eventually improve the design of various PFCs which are exposed to heat loads in the range of 100 kW/m^2–10 MW/m^2.

The detailed thermo-mechanical analysis of HHF divertor module TM-H09 shows no critical issues when it is subjected to 10 MW/m^2 stationary heat flux. However, the supports have to be optimized with an extra flexibility. Similar modules were also studied and confirmed by FE analyses based on simplified models.

FE calculations indicate that the tiles of baffles and heat shields can withstand average steady state heat loads of 250 kW/m^2. But, due to high thermal stress in the cooling pipes, the pulse length of plasma operation must be limited depending on the number of full load cycles. In order to predict the operation limit of W7-X more precisely, further heat flux tests with an increased number of cycles are necessary.

Several FE calculations were done for wall panels to investigate deformations. The results are the basis for the WP gap requirements for assembly. Further analyses are ongoing on the baffles, heat shields and wall panels with respect to allowed gaps and steps in between them, relaxation of support restrictions, and nonconformities.

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