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Effect of design geometry of the demo first wall on the plasma heat load

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ABSTRACT

In this work we analyse the effect of W armour surface shaping on the heat load on the W/EUROFER DEMO sandwich type first wall blanket module with the water coolant. The armour wetted area is varied by changing the inclination and height of the «roof» type armor surface. The deleterious effect of leading edge at the tiles corner caused by misalignment is replaced in current design by rounded corners. Analysis has been carried out by means of the MEMOS code to assess the influence of the thickness of the layers and effect of the magnetic field inclination. Calculations show the evolution of the maximum temperatures in the tungsten, EUROFER, Cu allow and the stainless-steel water tube for different level of surface inclination (chamfering) and in the case of rounded corners used in the current design. It is shown that the blanket module materials remain within a proper temperature range only at shallow incident angle if the width of EUROFER is reduced at list twice compare with the reference case.

1. Introduction

The thermal energy stored in the DEMO1 inductive operation is about four times higher than in ITER. Therefore in DEMO energy density deposition to the first wall (FW) panels, divertor plates etc. will be much higher than that foreseen in ITER [1]. A strong erosion of the plasma facing components (PFC) is expected, particularly during the type I ELMs. To avoid an excessive heating and consequent thermal erosion during the heat loads in DEMO operation the plasma facing panels of the first wall (FW) blanket modules are profiled. The effect of leading edge unavoidable occurs due to finite misalignment of panels during maintenance and construction and brings to overheating of the panels corners. The mitigation of the inter-cassette misalignment consequences by chamfering the plate is considered.

The appropriate rounding of the corners foreseen in the current panel design decreases the wetted area. The most severe distraction can occurred where the magnetic field lines intersect the FW. The engineering heat loads can be tolerable only in case of rather shallow magnetic field incident angles. A parametric analysis has been carried out to assess the influence of geometrical and thermo-hydraulic parameters on the FW module. For this purpose the MEMOS code is employed [2]. As a FW plasma facing module we analyse the W/EUROFER sandwich type structure with water coolant stainless steel tube surrounded by Cu allow as a compliance layer. First, we consider the reference FW blanket module with and without armour surface inclination and then the rounded panels design. Then the expected power fluxes under DEMO1 stationary operation are considered. The nominal power fluxes along the magnetic field at the FW blanket modules are expected about 50 MW/m^2. In the current design and averaged incident angle about 3–4.5° (similar to ITER) the engineering power load to the FW is expected within 2.5/3.9 MW/m^2. In the case of the unmitigated Type I ELMs which are unavoidable in the higher confinement H-mode of operation energy load per ELM is about 20 MJ/m^2 along the field line, arriving at a frequency of 0.8 Hz with deposition time of 0.6 ms per each ELM. Then the maximum temperature of tungsten castellated armor surfaces for the PFC for several scenarios of expected in DEMO I operation conditions is analyzed. To minimize the power impact the armour wetted area is varied by changing the inclination and height of the «roof» type armor surface. Calculations show the distribution of energy and the evolution of temperature in the bulk of W armour as well as the consequent surface melting for different values of wetted area. An expected level of erosion for optimal inclination and technically acceptable shape of the considered sandwich type blanket module is estimated.

First we will consider the reference design of the FW blanket module which faces plasma. Then the heat fluxes to the FW during steady phases of operation are assessed. Finally, the effect

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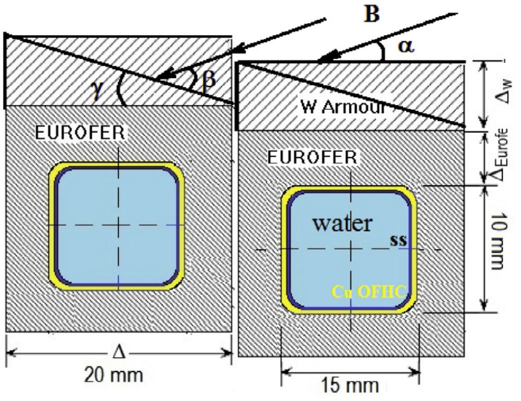

Fig. 1. The two adjacent cassettes of the DEMO FW blanket modules facing plasma; W armor with water cooling tube embedded into EUROFER with the compliance layers of Cu OFHC and stainless steel; inter-cassette misalignment is shown; the leading edge can be avoided by proper inclination of the plasma facing surfaces, $\gamma > 0$; α is the pitch angle, $\beta = \gamma + \alpha$.

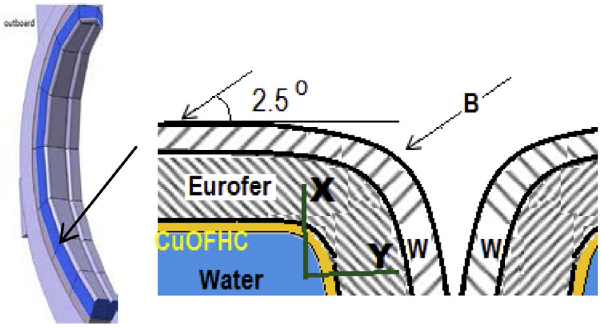

Fig. 2. The first wall outboard segment is shown (on the left) and a bending in the tiles corners of the FW (on the right). The whole segment consists of 14 toroidal oriented panels. The figures are not in scale.

on incident angle, misalignment and surface chamfering and effect of rounded panel's corner are discussed.

2. Design of the FW blanket module facing plasma

The two adjacent cassettes of the DEMO FW blanket modules facing plasma are shown in the Fig. 1. The parameters of the module chosen for calculation are as Cu alloy compliance layer has a thickness 1 mm and stainless As a reference case we consider the W armor layer thickness $\Delta_W = 2$ mm and for EUROFER $\Delta_{Eurofr} = 3$ mm. with water cooling tube embedded into EUROFER with the compliance layers of Cu OFHC and stainless steel; inter-cassette misalignment is shown. It is shown how the leading edge can be avoided by proper inclination of the plasma facing surfaces, $\gamma > 0$. Cu alloy compliance layer has a thickness 1 mm and stainless steel - 0.4 mm. This geometry with a flat armor surface is considered in our calculation as the reference case. (see Fig. 1).

The inter-cassette misalignment (maximum up to 3 mm) between two segments shown in Fig. 1, is one of the critical issues for DEMO and ITER, because it creates the leading edges on the FW structures with very small wetted areas. The pitch angle $\alpha \sim q_{edge}$ R/ a in DEMO is expected to be about 4.5–5° and corresponds to heat incident angle for a flat tile. Here we use $R = 8.8$ m, $a = 2.8$ m and $q = 3.5$ which corresponds to DEMO1 design. The edge chamfering considered here with an armor surface inclination, $\gamma > 0$, allows one to avoid the leading edge formation (see Fig. 1) and could lower the engineering (normal to the plane) heat load ~ sin $(\gamma + \alpha)$ times. In the Fig 2 the first wall outboard segment is shown. The whole segment consists of 14 toroidal oriented panels. A bending in the corners of the FW is taken into account and shown ion the right side of Fig. 2. The toroidal gap between segments (distance kept parallel along the segment) is 20 mm. The poloidal gap between modules (distance kept parallel along module) is10 mm.

Thermo-hydraulic analysis of the DEMO FW module with the tungsten armor and a water cooling channel embedded into EUROFER is performed by using the code MEMOS [2], which simulates the temperature of materials under the heat loads. The water cooling in DEMO has to be more efficient by removing much higher heat than in ITER. To stay within the allowed temperature window for materials the pressurized water reactor (PWR) like water cooling conditions with inlet temperature 325 °C, pressure 15.5 MPa and velocity in the range of 20 m/s is used [3]. The decrease of water temperature from 325 °C typical for PWR to 295 °C corresponds to increase of the critical heat flux (CHF) up to 37 MW/m^2.

First we analyze the required thicknesses of armor and other layers in blanket module for operating the materials within the allowable range. The upper temperature for W is limited by recrystallization (1573/1773 K) and for EUROFER by creep strength, common to RAFM steels (573/823 K). The low limits are determined for both materials by ductile to brittle temperature transition (DBTT) [4]. The upper allowable temperature boundary for the Cu alloy Cu oxygen free high conductivity material Cu OFHC is limited by the low thermal creep at temperatures above ~ 0.5 T_m, where $T_m \sim 1356$ K is the melting point. Since the pipe is reinforced by the stainless steel inner tube, the Cu alloys could sustain the slightly higher temperatures mentioned above. Cu alloy characterized by high ductility, good creep resistance and thermal conductivity. Since, however, there is no reliable data of thermo-mechanical properties under irradiation expected in DEMO, we follow [4], assume 20% of degradation of thermal conductivity in Cu OFHC and 10% in EUROFER and W, which corresponds to irradiation of ~5 dpa.

3. Power fluxes to the FW during steady phases of operation

3.1. The base static plasma heat load at top phase

A last baseline DEMO1 configuration [1] with the aspect ratio $k = 3.1$ and 18 TF coils ($R = 8.8$ m, $a = 2.8$ m, $B = 5.4$ T, $q_{edge} = 3$, $Ip = 19.5$ MA, S the surface area~1331 m^2) and the fusion power of $P_f = 2$ GW is considered here. According to the PROCESS code calculation 2 h burning can be achieved with $P_{add} = 50$ MW of additional power resulting in about $P_{exh} = 450$ MW of thermal power exhaust in the nominal operation [1]. The LH threshold power P_{LH} is estimated as 130 MW [1]. Therefore, the maximum radiation from DEMO bulk plasma cannot exceed ~71% (~320 MW) and in this case the minimum heat power crossing the separatrix in particles is about $P_{sep} = 130$ MW. The PROCESS code gives $P_{sep} \sim 149$ MW, which corresponds to about 67% of radiation from the balk DEMO1 plasma. Whether such a level of radiation can be achieved in the reactor plasmas remains unclear. Therefore, we assume here that like in ITER about 25% of power is radiated from the balk DEMO plasma ($P_{rad} \sim 113$ MW); then, the power crossing the separatrix is $P_{sep} \sim 340$ MW. In our estimations further we will use this value as a reference case. Then, the parallel heat flux along the magnetic field lines at the separatrix outer mid-plane can roughly be estimated as $(P_{sep}/S) \cdot \pi q_{edge} Rk/\lambda \sim 0.1\text{–}2.0\ GW/m^2$, depending on the power decay length λ in the near SOL region. Here we assume single null x-point divertor and assessments will be done for the outer mid-plane with two separatrix, corresponding to lower and upper second x-points. The e-folding length in the near SOL depends mainly on the electron parallel thermal conductivity and the SOL connection length. It scales as $\lambda \sim T_s \cdot \sqrt{R q_{edge}}$

and for separatrix electron temperature $T_s \sim 3$ keV and density $\sim 0.36\ 10^{20}\ \mathrm{m}^{-3}$ can be estimated in the range of 0.01 m. This will reduce the parallel heat flux at the near SOL in $\exp(-r/\lambda)$ times down from the tenth to several MW/m^2.

3.2. *Power flux to the DEMO FW due to the "blobs"*

For the far SOL region the radial transport dominates by turbulence, which causes the fast radial convection of "blobs", and leads to the appearance of long "shoulders" in the parallel heat profiles in radial directions predominantly in the outer SOL due to ballooning nature of the turbulence. The same phenomenon in the far SOL of DEMO boundary could be expected, particularly for higher density foreseen in a reactor. The radial convective velocity u of the blobs in the outer SOL is weakly dependent on device size and can be assumed for DEMO as $u \sim 30$–100 m/s similar to ITER [5]. Taking into account that the transport in the far SOL is mainly convective allows one to estimate the power decay length at the outer mid-plane as $\lambda_m \sim 0.1$–0.2 m. The parallel power fluxes reduction at the outer FW wall can be estimated as a double exponential fall. The calculation shows that for the DEMO SOL conditions the reduction is the same as in ITER [6]. The expecting range of the parallel heat flux at the FW is about 30–50 MW/m^2. Here we assume that the FW is in average separated from the separatrix on ~25 cm. Normal to the FW surface load (engineering heat load) will depend on incident magnetic field angle and for the angles ~2–5° can be roughly expected in the range of 1–3 MW/m^2 (without ELMs). Compared with these loads the power fluxes to the FW due to radiation and charge-exchange neutrals are of order magnitude lower.

3.3. *Power fluxes to the DEMO FW due to radiation and charge-exchange neutrals*

The DEMO FW will be subject to energy and power fluxes associated with plasma radiation and charge-exchange neutrals. The maximum radiation can be estimated as $P_{\mathrm{rad}} = P_{\mathrm{exh}} - P_{\mathrm{LH}} = 370$ MW which includes the 10% of error [1]. Then the average photons load is about 0.28 MW/m^2. An upper limit for power fluxes by charge exchange neutrals can be derived by assuming that at least half of injected neutrals undergo the charge exchange (c.x) and bring the boundary temperature (~3 keV) to the wall. The injected ion flux derived from the particle balance equation in burning plasma is expected to be $1.1 \times 10^{23}\ \mathrm{s}^{-1}$ [7]. This corresponds to the c.x power flux to the FW of about 0.02 MW/m^2. Taking into account strong poloidal asymmetry at the outer side of the device, where gas puffing port is located similar to the ITER design, the maximum power flux on the DEMO wall can be estimated as 0.16 MW/m^2 for peaking factor (~8) like in ITER.

3.4. *Power flux to the DEMO FW due to the ELMs*

The edge localized modes (ELMs) deposition on the DEMO first wall is assumed to be about 5–20% of the ELM energy lost from the main plasma [8] and can be estimated for the unmitigated ELMs as $\geq 20\ \mathrm{MJ/m^2}$ for deposition at the upper X-point and about 15 MJ/m^2 at the outer mid-plane by accounting for the radial propagation of filaments towards the wall [9]. It is also assumed that the ELM deposition time on to the FW is about half of that on outer divertor and is about 0.6 ms [8]. The ELM ions can load magnetically shadowed regions (poloidal and toroidal gaps can be overloaded by the ELM impact).

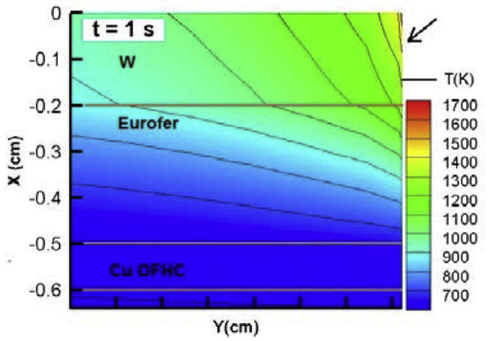

Fig. 3. The temperature distribution inside the FW tile with leading edge after exposition of parallel heat load of 50 MW/m^2 during 1 s.

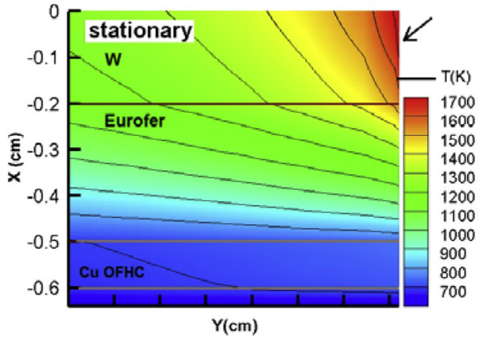

Fig. 4. The temperature distribution inside the FW tile with leading edge in the case of stationary operation under exposition of parallel heat load of 50 MW/m^2; The PWR like conditions with inlet temperature 325 °C.

4. Results of calculation and discussion

4.1. *Effect of misalignment and inclination of the plasma facing surfaces*

The effect of misalignment and leading edge on overheating of the tile is calculated. The 2D temperature distribution in the cassette tile after 1 s of heat deposition is shown in the Fig. 3 and in the stationary case in Fig. 4. The 50 MW/m^2 power flux is hitting the leading edge from the right side (see Fig. 1) at $\alpha = 4.5°$ incident angle against the horizontal plane.

The misalignment between the left and right cassette is taken like in ITER as 1.5 mm. After 1 s of heat deposition W armor right corner is heated up to 1500 K and the temperatures of EUROFER and Cu alloy exceed the upper allowable limits (see Fig. 3). In the stationary operation armor temperature at the right corner reaches 1700 K (see Fig. 4) and a recrystallization of W can be expected. The other materials can also experience creep deformation under mechanical forces. Apart from that a strong temperature gradient in the tile can cause thermal stresses.

To avoid the misalignment problems the inclination of the plasma facing surface plate is considered. Effect of plate inclination on the maximum temperature is shown in Fig. 5.

As it seen from calculation for expected pinch angle $\alpha = 4.5°$ a slight inclination of the plate $\gamma \leq 3.5°$ allows to avoid a leading edge overheating and possible melting. Indeed, as it is seen from the Fig. 5 the W temperature remains within allowable range, when the sum of incident and inclination angels remains $\leq 8°$. Calculation was carried out for 50 MW/m^2 of stationary power load.

4.2. *Effect of rounded panel corners*

The temperature distribution along the rounded panel edges are shown in the Fig. 6. For typical accident angle 2.5° and at about

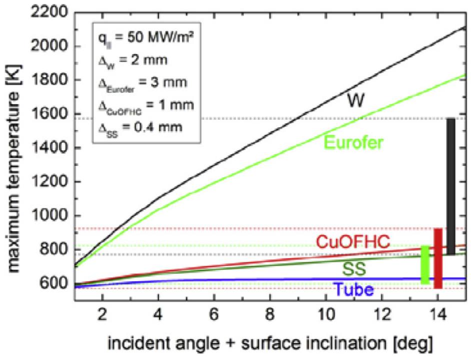

Fig. 5. Evolution of the maximum material temperature vs incident angle and the plate inclination $\gamma+\alpha$.

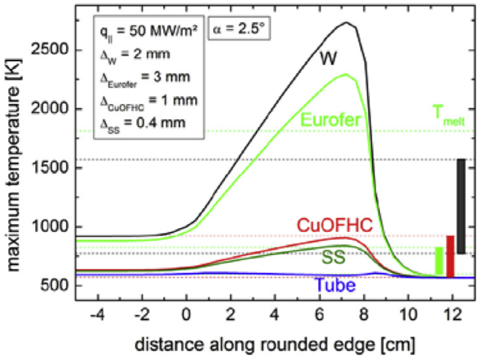

Fig. 6. The maximum temperature of materials along the rounded panel corner. Edge radius is 187 mm, gap between segments is 20 mm. The thicknesses of materials are taken as for the reference design case.

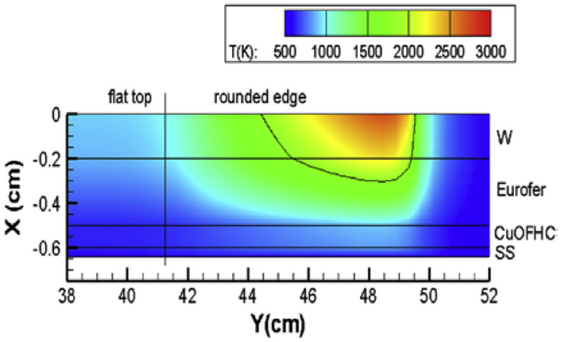

Fig. 7. The 2D contour plot of isothermals at the rounded surface of segment corner. Black curve separate the EUROFER layer from tungsten armor.

6 cm from the flat top surface the tungsten temperature still exceed the upper limit and the EUROFER temperature is above the melting point. Therefore the rounding the panel corners cannot help from overheating.

This result has also shown in Fig. 7 where the 2D contour plot shows isothermals at the melting temperature of EUROFER.

4.3. Effect of ELMs

The evolution of the maximum material temperatures for heat loads including ELMs are shown in Fig. 8 and Fig. 9 for different impact angles 4.5° and 3.0° and for reference module geometry with 2 mm W, 3 mm EUROFER, 1 mm Cu OFHC, and 0.4 mm SS. The stationary heat load along magnetic field line is 50 MW/m². The energy per ELM is 20 MJ/m², arriving at a frequency of 0.8 Hz and the deposition time of each ELM 0.6 ms. The ELM energy also flows along the magnetic field lines and is projected to the plate.

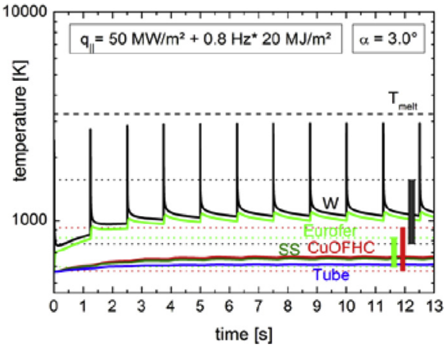

Fig. 8. Evolution of the maximum material temperature during the Type 1ELMs impact with parallel stationary heat load 50 MW/m² and energy load per ELM of 20 MJ/m², arriving at a frequency of 0.8 Hz. The deposition time of each ELM is 0.6 ms. Pitch angle 3.0°. The W armor does not melt.

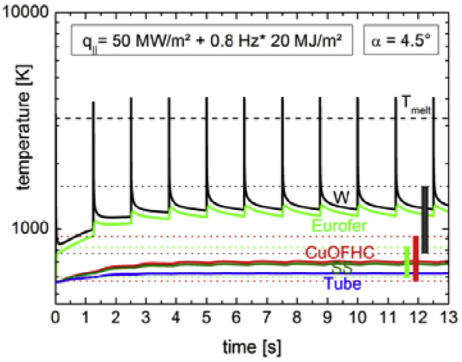

Fig. 9. Evolution of the maximum material temperature during the Type 1ELMs impact with parallel stationary heat load 50 MW/m² and energy load per ELM of 20 MJ/m² arriving at a frequency of 0.8 Hz. The deposition time of each ELM is 0.6 ms.

Calculation shows that for $\alpha=3.0°$ case the impact of the repetitive ELMs is tolerable (See Fig. 8). No armor melting occurs, however the maximum temperatures for tungsten armor () and EUROFER () exceed the upper allowable limits. For a slightly increased incident angle $\alpha = 4.5°$ the W armor melts at the ELM peak positions and solidifies between the ELMs. The mitigation of the Type 1EMLs seems to be mandatory.

Conclusions

In steady-state DEMO operation without ELMs and under PWR water cooling conditions the FW blanket module with tungsten armour width ~2 mm and the EUROFER width ~ 3 mm can tolerate expected heat loads only at rather shallow incident angles ≤ 2° of the parallel heat flux to the armour surface.

The effect of leading edge due to a misalignment causes a strong overheating of the tiles corner. The rounding of the tails prevents from W melting, but EUROFER remains still in higher temperature range.

The blanket module materials will remain within a proper temperature range ≤ 4° of incident angle if the width of EUROFER is reduced at list twice compare with the reference case.

Under operation with ELMs at shallow incident angles (≤ 3°) no armour melting occurs. However the maximum W temperature at peak ELM positions exceeds the upper allowable limit which can cause recrystallization. The EUROFER temperature is also exceeds the maximum limit thus lowering the creep strength. This confirms that the mitigation of the EMLs in DEMO is mandatory.

Acknowledgments

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