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Thermomechanical simulation of WEST actively cooled upper divertor

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ABSTRACT

The Tore Supra tokamak is being transformed in an x-point divertor fusion device in the frame of the WEST (W-for tungsten-Environment in Steady-state Tokamak) project, launched in support to the ITER tungsten divertor strategy. The WEST project aims to test ITER-like W monoblock Plasma Facing Units (PFU). This ITER-like divertor will be tested under long plasma discharge up to 1000 s, with high heat flux density up to 20 MW/m^2. This paper presents the results of ANSYS thermal-structural simulations of the WEST upper divertor. The upper divertor is made of twelve 30° sectors, each one composed of 38 PFU. The PFUs are actively cooled CuCrZr heat sinks and the incidence surface is coated with a thin tungsten layer. The fixing system is made of pins engaged in slotted holes. Besides, the fixing system of the sector assembly is the same as WEST lower divertor, so one upper divertor sector can be used indifferently in upper or Lower position during transitional operation phases in WEST. The total surface of the upper divertor is 8 m^2, and it has to be able to extract up to 4 MW in steady-state, with peak heat flux values up to 8 MW/m^2. The fixing system was designed to handle structural loads such as forces and torques resulting from halo and eddy current, respectively, especially during disruptions and Vertical Displacement Event (VDE). The torque resulting from eddy current is first calculated thanks to an internal CEA ANSYS APDL routine. Then the ANSYS structural and thermal-structural simulations of the PFU are presented, and its design is validated thanks to A-level RCC-MRx criteria. Finally, the most conservative load case is determined in order to validate the design of the pins and the support structure.

1. Introduction

Tore supra is a tokamak using superconducting magnets. It was designed to carry out long plasma operations, so it uses actively cooled plasma facing components. The WEST project aims to transform Tore Supra from a limiter configuration to an X-point configuration in order to validate the technology of a full tungsten ITER-like actively cooled divertor [1].

The WEST upper divertor is actively cooled and is made of CuCrZr (Treatment B according to [8]) heatsinks covered with a tungsten coating. Its design and structural analysis were done taking into account electromagnetic, thermal and structural loads as well as assembling and disassembling constraints. The different simulations showed that the actual design can handle the different load cases.

The total surface of the divertor is 8 m^2, and it has to be able to extract up to 4 MW in steady-state, with peak heat flux values up to 8 MW/m^2. The fixing system was designed to handle structural loads such as forces and torques resulting from halo and eddy current in the PFU during disruptions and Vertical Displacement Event (VDE, dBn/dt = 90 T/s for 10 ms).

2. The WEST upper divertor

The upper divertor is made of twelve 30° sectors, each one composed of 38 Plasma Facing Units (PFU), so there are 456 PFUs in total. The upper divertor is placed under the upper casing – which contains the upper divertor coils – and it is made of several components. The support is made of 12 30° sector, which are 316 L stainless steel conic plate on which 152 Xm19 stainless steel fixing elements (4 per PFU) are fixed. In each of this fixing element an Aluminium-Nickel-Bronze alloy (Al-Ni-Br) pin is engaged in a slotted hole, in order to allow thermal expansion in the length direction of the PFU. This alloy was chosen for its very good anti-seizing property. Moreover, the Xm19 and Al-Ni-Br alloy have high tensile stress compared to 316 L stainless steel, which is required because the Hertz pressure can be high in a pin engaged in a slotted hole. The PFUs are actively cooled CuCrZr heat sinks, and the

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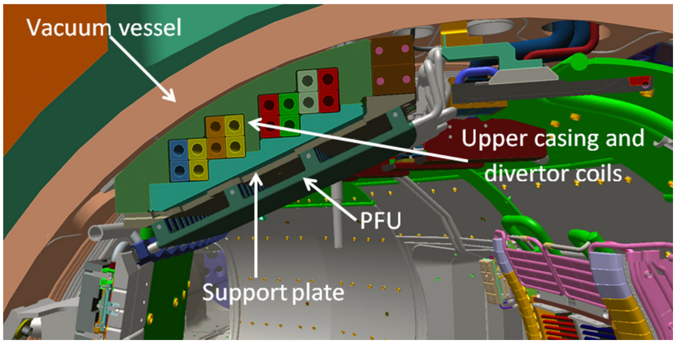

Fig. 1. The upper divertor in WEST (radial-poloïdal plane).

incidence surface is coated with a thin tungsten layer [3,6]. Each PFU has four pairs of legs in which the pin is pressed fit. Finally, each PFU cooling channel is welded to a 316 L stainless steel cooling pipe to ensure active cooling thanks to an Inconel ring. Besides, the fixing system of the sector assembly is the same as WEST lower divertor, so one upper divertor sector can be used indifferently in upper or lower position during transitional operation phases in WEST (Figs. 1 and 2).

3. Analysis

3.1. Design criteria

The operational thermal limits for the PFU are the following [6]:

- Maximum temperature T_{max} in the PFU 450 °C
- Maximum power extracted P_{max}: 12.5 kW in UP and 25 kW in LP (cooling system limit)
- Maximum heat flux on PFU channel Φ_{max}: 11.5 MW/m^2 in UP and 14.7 MW/m^2 in LP. The safety margin is 1.4.

For mechanical criteria, an RCC-MRx code design criteria were used for the WEST upper divertor [9]. This code is a set of technical rules applicable on the French territory for the construction and design of mechanical equipment of nuclear installation such as Sodium Fast Reactor (SFR), fusion reactor (ITER), research reactor (RR) and associated experimental devices.

An A level RCC-MRx criteria was used for all components. Fatigue and buckling RCC-MRx criteria were not considered in this analysis. The respect of these criteria prevents from excessive deformation and ratcheting. To respect those criteria, two analyses are required, a structural and a thermal-structural one. The criteria are applicable for the linearized stresses extracted from finite element elastic analyses. Linearized stresses are calculated along a supporting line segment, which is the shortest segment which joins two faces inside the component.

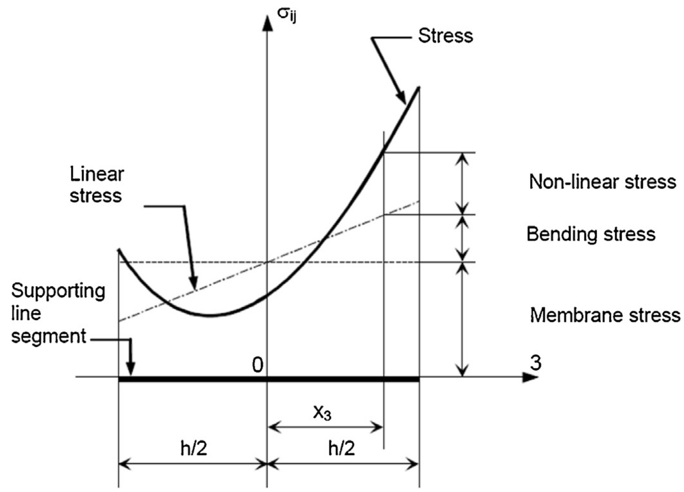

Fig. 3. breakdown of the stress along a supporting line segment with length *h* [9].

Two groups of linearized stresses are considered for RCC-MRx criteria: primary stresses and secondary stresses. The primary stress is the fraction of the total stress which does not disappear after small scale deformation (stresses which balance the mechanical efforts, pressure and forces for example). The different types of primary stresses are:

- Primary membrane stress: $\overline{P_m}$
- Primary bending stress: $\overline{P_b}$
- Local primary membrane stress: $\overline{P_L}$ (close to a geometrical loading or discontinuity)

The stress $\overline{P_m + P_b}$ is called the linear stress. Fig. 3 shows the breakdown of the stress along a supporting line segment.

The secondary stress is the fraction of the total stress which can disappear as a result of small scale deformation (thermal stresses or imposed displacement). The secondary stress is called Q.

The design criterion for RCC-MRx is the allowable stress S_m, and depends on the maximum temperature of the supporting line segment. In this case, S_m is defined as:

- $S_m = \min\left(\frac{2}{3}R^t_{p0.2}; \frac{1}{3}R_m\right)$
- $R^t_{p0.2}$ is the 0,2% offset yield strength considered at the maximum temperature of the supporting line segment

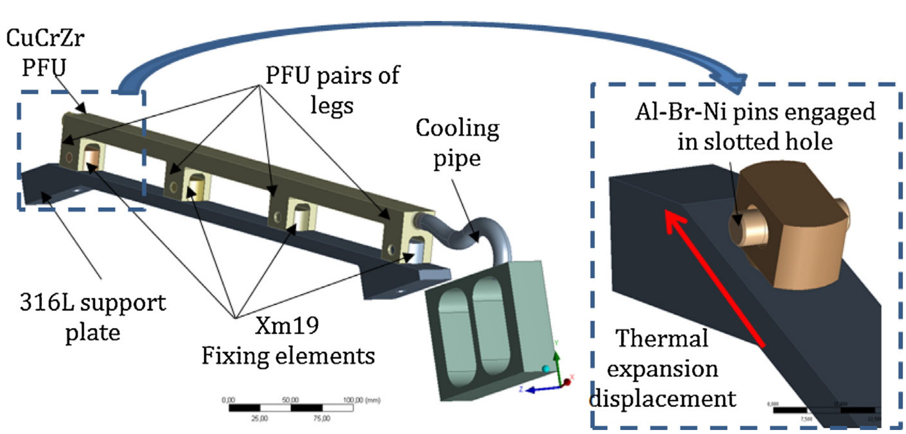

Fig. 2. Structure of the upper divertor for one PFU.