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ITER-like divertor target for DEMO: Design study and fabrication test

F. Crescenzi[a,*], H. Greuner[b], S. Roccella[a], E. Visca[a], J.H. You[b]

[a] ENEA, Unità Tecnica Fusione, ENEA C. R. Frascati, Via E. Fermi 45, Frascati, 00044, Roma, Italy
[b] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748, Garching, Germany

HIGHLIGHTS

- 'DEMO' is a near-term Power Plant Conceptual Study (PPCS).
- The ITER-like design was developed by means of a preliminary code-based design study.
- ITER SDC-IC were used to check structural failure of the optimized geometry.
- The first trial of mock-up fabrication using a new joining furnace at ENEA.
- The ultrasonic inspection test were made to confirm the high quality of fabrication.

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ABSTRACT

As a major in-vessel component of a tokamak-type fusion reactor, the divertor is mainly in charge of removal of particles and partial power exhaust via scrape-off layer. The target plate of the divertor is directly exposed to non-uniform high heat flux on the surface by particle bombardment and radiation. In the case of ITER and a DEMO reactor, the peak surface heat flux is expected to reach up to 10 MW/m^2 during normal operation and 20 MW/m^2 during slow transient events like loss of plasma detachment.

This paper reports the results of a preliminary code-based design study and fabrication technology verification test which were conducted for developing an ITER-like divertor target design for the DEMO divertor.

The structural failure evaluation against the ratchetting and fatigue criteria of the ITER SDC-IC showed that the design with reduced dimensions would allow sufficient design margin (reserve factor) for three distinct thermal loading cases. The first trial of mock-up fabrication using a new joining furnace at ENEA was successfully completed. The ultrasonic inspection test made before and after the cyclic HHF tests at GLADIS facility demonstrated high quality of fabrication and robust design concept.

1. Introduction

As a major in-vessel component of a tokamak-type fusion reactor, the divertor is mainly in charge of removal of particles and partial power exhaust via scrape-off layer. The target plate of the divertor is directly exposed to non-uniform high heat flux on the surface by radiation and particle bombardment. In the case of ITER and a DEMO reactor, the peak surface heat flux is expected to reach up to 10 MW/m^2 during normal operation and 20 MW/m^2 during slow transient events like loss of plasma detachment. The temporal fluctuation of temperature in the plasma-facing components (PFCs) lead to a variation of thermal stresses raising the risk of fatigue failure [1]. Neutron irradiation, which is predicted to be significant for the DEMO divertor (e.g. 13 dpa for copper heat sink after 2 fully power year), is an additional challenge for the engineering of divertor components since the damage of materials produced by irradiation may cause severe embrittlement at lower operation temperature [2].

In the frame of the EUROfusion Consortium launched in 2014, a preconceptual R&D program has been carried out in the Work Package 'Divertor' (WPDIV) to develop preconceptual basis for design solution and technologies [2]. In the subproject "Target development", the design concepts and engineering technologies are developed for the PFCs, in particular, the target plate. One of the 8 design concepts being currently considered in this subproject is the ITER-like tungsten monoblock target design developed originally for the water-cooled vertical target of the ITER divertor [3]. This ITER-like target design is adopted as a reference design model with which the other design concepts shall be compared in terms of ther-

* Corresponding author.
E-mail address: fabio.crescenzi@enea.it (F. Crescenzi).

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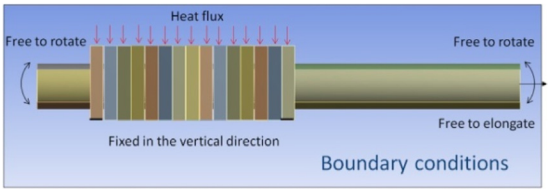

Fig. 1. A schematic view of a reference mock-up of the ITER-like divertor target design concept consisting of 15 tungsten monoblocks and a copper alloy cooling tube. Static boundary conditions are indicated.

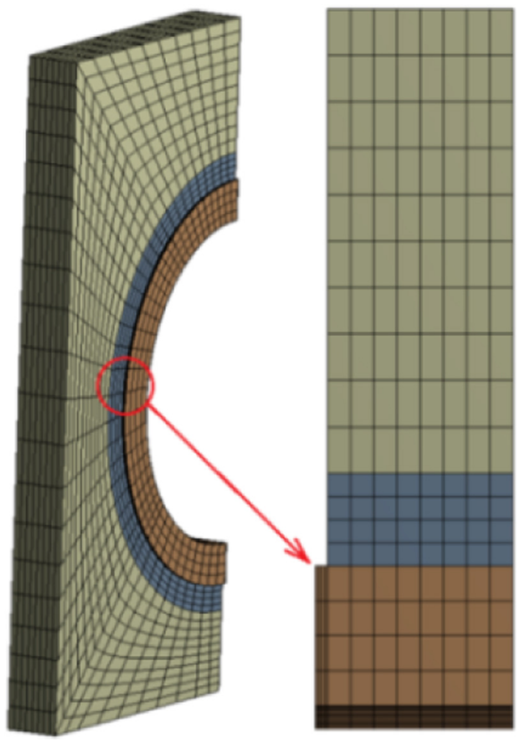

Fig. 2. FEA model (a symmetric quarter part of a single monoblock) and mesh.

mohydraulic and structural performances as well as manufacturing aspects.

In this paper, an overview on the preliminary studies of design optimization, mock-up fabrication and high-heat-flux (HHF) test is presented which was performed in the framework of the subproject 'Target' of WPDIV program. Emphasis is placed on the design optimization in terms of monoblock dimension and geometry.

2. Finite element model and boundary conditions

The design of the ITER-like divertor target component consists of an array of tungsten monoblocks as armor, a CuCrZr alloy tube as heat sink and a thick soft copper interlayer between the cooling tube and the monoblocks. Rolled tungsten and CuCrZr-IG (SAA cw) are used as baseline materials for the armor and tube, respectively. Hot radial press (HRP) technique has been applied as a reference joining method for manufacturing the ITER divertor target [3]. Likewise, HRP process was used also in this study for fabricating mock-ups. Each test mock-up consisted of 15 rectangular monoblocks each with a thickness of 4 mm and a gap of 0.25 mm between two neighboring monoblocks. Considering actual kinematic constraints, equivalent static boundary conditions were applied for the computational simulation (see Fig. 1).

Fig. 2 illustrates the model geometry created for finite element analysis (FEA). For the linear elastic FEA-based optimization study the commercial Design Exploration package of ANSYS 16.2 Workbench was used. Only a symmetric quarter part of a single block was modelled. The FEA mesh consisted of 6400 elements (the element type SOLID186) and 30,000 nodes.

The thermohydraulic boundary conditions were defined considering following design requirements [4]:

1. The specified maximum local surface heat flux is 20 MW/m^2. The thermohydraulic design of cooling was adapted to this transient peak heat flux load.

2. The reference heat flux considered for structural design optimization study is 10 MW/m^2 that is the quasi-stationary load expected for the normal operation.

Structural failure at the transient peak load of 20 MW/m^2 was also investigated in terms of plasticity fatigue and fracture mechanics, but published elsewhere [5].

3. The local maximum coolant water temperature at the strike point is set to 150 °C (or lower) in order to attain a sufficient safety margin to the critical heat flux (CHF) at the cooling tube wall. The minimum required safety margin to CHF is 1.4.

4. The associated coolant pressure and local minimum velocity is set to 5 MPa and 16 m/s, respectively. Current cooling condition causes only slight pressure drop and thus requires low pumping power.

It could be necessary to reduce the coolant temperature and velocity to prevent corrosion or erosion of the inner tube (e.g. to <130 °C and <11 m/s). However, the prominent irradiation embrittlement of the structural heat sink material at lower temperature (<200 °C) should be also taken into account.

The thermal analysis needed for the stress analysis in the structural design optimization process was carried out for the reference heat flux of 10 MW/m^2. The heat transfer coefficient was calculated using the Sieder-Tate and the empirical Tong-CEA correlations [6,7].

3. Parametric design optimization

The geometrical parameters which were considered as optimization variables were [8]:

i) The inner diameter of the CuCrZr cooling tube,
ii) The thickness of the cooling tube,
iii) The thickness of copper interlayer,
iv) The side minimum thickness of the W block.

The objective function to be minimized was:

i) The maximum temperature in the cooling tube,
ii) The maximum von Mises stress in the cooling tube.

The armor thickness from the surface to the interlayer was fixed at 5 mm. The influence of the varying armor thickness on the thermal and structural performance was studied elsewhere [5]. The optimized dimensions are as follows:

Tube inner diameter: 12 mm
Tube thickness: 1.5 mm
Interlayer thickness: 1 mm
Armor side thickness: 3 mm

4. Thermal and structural design studies

It is important to note that the results of computational stress analysis are essentially affected by the numerical quality and modelling assumptions. In the framework of WPDIV, standard technical guidelines for FEA of stress were produced in order to provide a dedicated simulation strategy for the ITER-like monoblock type joined