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Systems engineering approach for pre-conceptual design of DEMO divertor cassette.

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This paper presents the pre-conceptual design activities conducted for the European DEMO divertor, focusing on cassette design and Plasma Facing Components (PFC) integration. Following the systems engineering principles for the conceptual stage, high level design requirements are collected and conceptual 3D model of divertor's cassette is presented. The work moved from the geometrical and interface constraints imposed by the 2015 DEMO configuration model. Then, since different materials will be used for cassette and PFCs, the divertor geometry has been developed taking into account the cooling parameters of the cassette Eurofer steel and the integration of PFCs cooling system. Accordingly, the design process led to a double wall cassette structure with internal reinforcing ribs to withstand cassette coolant pressure and three different kinds of piping schemes for PFCs with dual circuits. These three solutions differs in the feeding pipes layouts and target manifold protection and they have been proposed and evaluated considering heat flux issues, shielding problems, interface requirements with blanket and vacuum vessel and remote maintenance needs. A cassette parametric shell model has been used to perform first structural analyses of the cassette body against coolant pressure. Taking advantages of the parametric surface modelling and its linkage with Finite Element (FE) code, the cassette ribs layout and thickness has been evaluated and optimized, considering at the same time the structural strength needed to withstand the coolant parameters and the maximum stiffness required for cassette preloading and locking needs.

Keywords: DEMO, divertor cassette, divertor cooling, divertor structural analysis

1. Introduction

One of the most relevant challenge in the development of next generation fusion reactors is the power exhaust and transmission from in-vessel components. The improvement to the divertor cooling system design as well as its remote maintenance devices are crucial to deal with such needs in the Demonstration Fusion Power Plant (DEMO), where high heat flux has to be continuously removed from the Divertor Target.

Since 2015 pre-conceptual design activities of DEMO divertor cassette have been carried out in terms of cassette design and PFCs integration within the divertor project (WPDIV) in the frame of EUROfusion consortium [1].

Systems Engineering principles have been adopted for cassette conceptual design, in order to meet different requirements from the interfacing Work Packages (WP) and to allow easy change of the design in the optimization processes [2] (Fig. 1).

The work moved from the geometrical and interface constraints imposed by the 2015 DEMO configuration model (Fig.2). Then, since different materials will be used for cassette and PFCs, the divertor geometry has been developed taking into account the cooling parameters of the cassette Eurofer steel and the integration of PFCs cooling system.

According to systems engineering principles, several design solutions for divertor cassette and PFCs integration have been developed and evaluated against structural and interface requirements within the divertor design team.

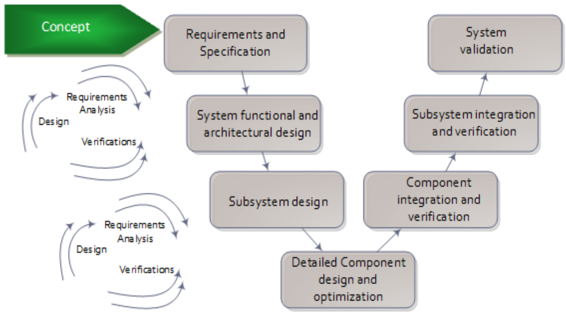

Fig. 1. System Engineering approach.

In this paper such pre-conceptual divertor design activities are described. The aim is to discuss the different proposed solution and to highlight the main points arisen in the decision-making stage to support further development of DEMO divertor.

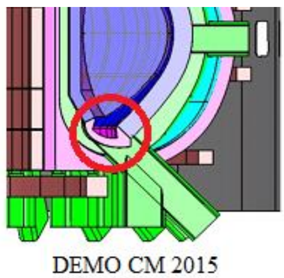

Fig. 2. 2015 DEMO Configuration Model.

2. DEMO Divertor Cassette body Design

DEMO divertor cassette pre-conceptual design has been developed starting from few high-level design requirements:

- Interfaces with blanket and vessel
- Inlet cooling water at 3,5 MPa (Table 1)
- Integration of PFCs cooling system
- Need to preload cassette to ensure electrical connection
- Eurofer technological limit: 40mm maximum thick plates

The cassette surface model [Fig. 3a] has been developed in CATIA V5 surface environment using a parametric approach, in order to allow easy change of ribs position and thickness during analyses optimization process [4] . From this, the solid model [Fig. 3b] has been derived, directly linked to the surface one.

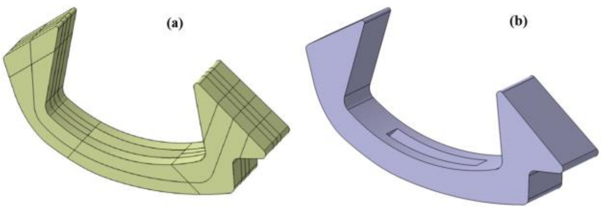

Fig. 3. (a) Cassette surface model, (b) solid model.

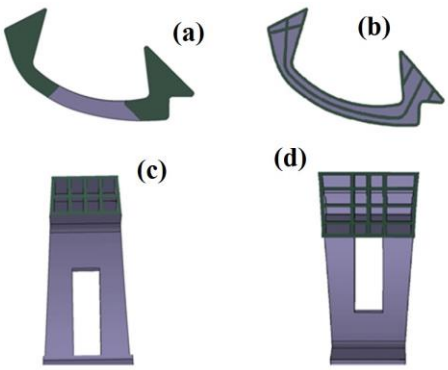

Fig. 4. Cassette body sections.

Cassette body is composed by an upper plate, a lower plate, side ribs and internal toroidal and poloidal ribs [Fig. 4] [Fig. 5]. The coolant goes in and out of the cassette from the outboard through two inlet/outlet pipes passing through lower port. In Fig. 5b it is shown the coolant path along radial direction.

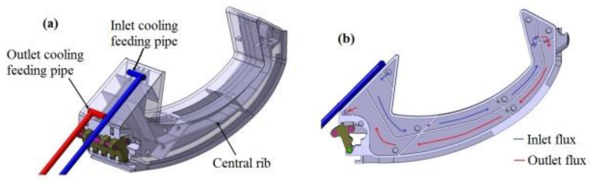

Fig. 5. (a) Internal cassette structure, (b) path followed by the coolant, the central poloidal rib separates the inlet and outlet fluxes inside the cassette.

Divertor Cassette Body	Inlet	Outlet
Pressure [MPa]	3.5	3.43
Temperature [°C]	180	210
Mass flow rate [Kg/s]	718	

Table 1. Cassette cooling parameters.

Dimensions chosen for the external shell and internal ribs are shown in Fig. 6. Ribs are fitted with holes to allow the coolant flow through the cassette. The diameter of the holes is 70 mm almost everywhere except in the small section at the outboard where the diameter is 40 mm. Such dimensions and feeding pipes positions are optimized according thermos-hydraulic analyses, cooling parameters and preloading needs.

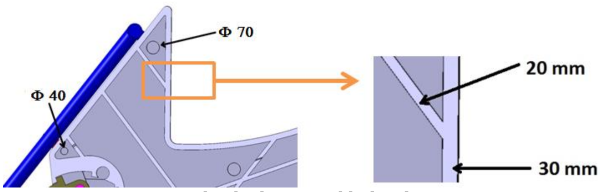

Fig. 6. Ribs thickness and holes diameters.

In interaction with Work Package Remote Maintenance team (WPRM), external ribs have been added on the lower plate to protect PFC cooling pipes in the case of a lifting platform cassette transportation concept [5].

3. PFCs cooling solutions

The PFCs cooling circuit is external to the cassette body. The pipes exposure to neutron damage is one of the main issue in the design process, as well as the interfaces between feeding pipes and fixation systems. Meanly three PFC cooling options have been developed differing essentially in the position of the pipes and manifolds on the cassette upper plate.

3.1. Cooling layout option 1

Option 1 [Fig. 7] is characterized by two choices: the presence of PFCs cooling feeding pipes that pass through the vacuum pumping hole and the presence of two manifolds in the bottom side for both inner and outer vertical target, for a total of four manifolds. Each pair of manifolds is used to collect the coolant necessary to PFCs cooling.

Fig. 7. First cooling configuration option. The colour of the pipes depends on their role: blue for inlet pipes, red for the outlet ones.

In this configuration manifolds are coupled together and are inserted into an appropriate C-shaped slot in order to protect them from the heavy radiation level inside the Vacuum Vessel.

Advantages

- Minimize interferences with supporting system, blanket and RH devices due to the position of cooling pipes and manifolds.

Disadvantages

- Pipes and manifolds are exposed and need to be shielded (the presence of a Dome is not clearly defined at time).

3.2 Cooling layout option 2

The second configuration option [Fig. 8] differs to the option 1 in the fact that the inlet and outlet manifolds are not "coupled", and they are placed respectively below and above the vertical targets.

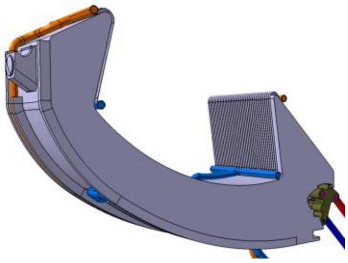

Fig. 8. Second configuration option.

In this configuration the vacuum pumping hole is crossed by two inlet pipe sections (instead of four) located in the middle of the hole. The inboard outlet feeding pipe goes along the whole cassette body to connect the inboard outlet manifolds located in the region between Divertor and the Blanket.

Advantages

- Uniform cooling of target PFC units (pipes do not make loops).
- The cooling temperature at the strike point is lower than the other two options, so that the Critical Heat flux is well dispersed.

Disadvantages

- Both inboard/outboard inlet manifolds need to be shielded.

3.3 Cooling layout option 3

In the third configuration option [Fig. 9] inlet and outlet manifolds are coupled and placed above vertical targets, in the region between the cassette and the blanket. Each outlet manifold is split into two smaller manifolds, so that inlet pipe can pass between them, and they are fed by two pipes passing below the cassette. Those pipes are joined by a manifold located in the lowest outboard region. The pipe connected to the inner inlet manifold also passes below the cassette, and joins other inlet pipes in the bottom outboard region of the cassette.

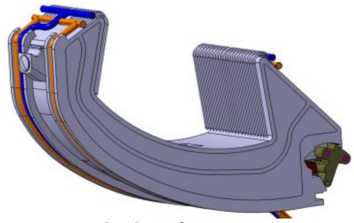

Fig. 9. Third configuration option.

Advantages

- Manifolds are properly shielded by the blanket.

Disadvantages

- Interfaces with blanket, supporting system and RH tools.

4. Cassette Fixation solutions

The main functions of the DEMO divertor cassette-to-vacuum vessel locking system is to provide a remote-handling-compatible means of locking and unlocking of the cassette. The system aims to provide reliable fixation of the DEMO divertor cassette in the vacuum vessel (VV), under different thermal and electromagnetic loads, during the operational mode of the reactor [6]. According to the systematic design process presented in [2], authors, in close interaction with the WPRM team, improve the fixation design solutions presented in [6] and [7] according to updated requirements and interfaces. Mainly two fixation options have been proposed and evaluated [Fig. 10].

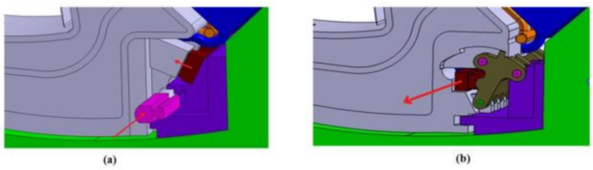

Fig. 10. (a) Fixation option 1, (b) Fixation option 2 (ITER-Like).

During toroidal transportation, clearances between pipework and the blanket shall be ensured to avoid collisions. When the divertor reaches the final position the fixation system lifts the cassette of 30mm along z axis to close the gaps between blanket and the cassette [Fig. 11].

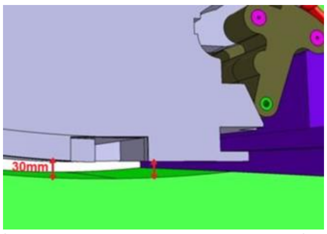

Fig. 11. The fixation system should be able to lift the cassette of 30mm along z axis when the cassette is in position.

In both fixation options proposed the cassette is preloaded to ensure electrical continuity and to remove clearances. Cassette preloading is achieved in both cases by an ITER-like hydraulic jack. A structural analysis has been performed assuming a preloading force of

100kN (ITER-like preloading). The result is a displacement of 0.7mm along preloading direction (the line passing through outboard fixation system and the centre of the nose).

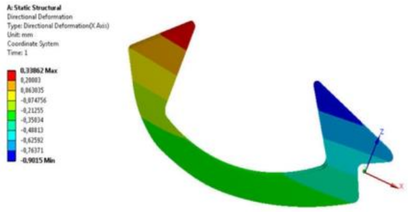

Fig. 12. Static structural analysis result considering a force of 100kN along preloading direction.

Some evaluation needs to be performed to understand if such a preloading is enough to clearance removal and electrical connection during shaking.

5. Pipes integration at lower port

An assessment of pipes integration at lower port level has been considered in collaboration with the Blanket and In-vessel integration team.

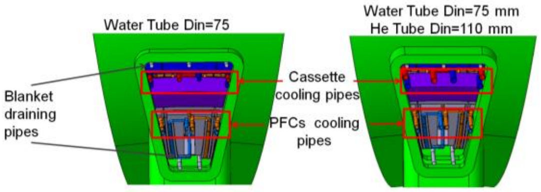

Fig. 13. Pipes integration at lower port.

Since cassette and PFCs are cooled by two distinct circuits, four pipes are required for each cassette (two for PFCs cooling and two for cassette cooling), so a total of 12 pipes pass through the lower port for divertor cooling (three cassette for each sector). In addition, at time there are other five blanket draining pipes passing through lower port in the configuration model [3].

The assessment has been carried on considering two distinct divertor pipes, corresponding on two cassette cooling options (Fig. 13) : water cooled cassette (D_{in}=75mm) and helium cooled cassette (D_{in}=75mm for water pipes and D_{in}=110mm for helium pipes).

Furthermore, integration with Helium and water cooled blanket pipes at lower port is ongoing, showing critical interface issues to be fixed (Fig. 14).

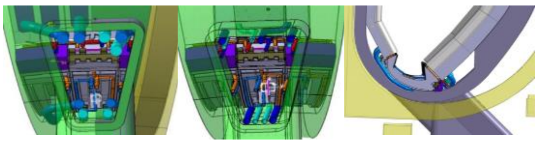

Fig.14 Integration of divertor and blanket cooling pipes at lower port.

Conclusions

Pre-conceptual design of DEMO divertor cassette body, PFCs integration and fixation system have been discussed. According to systems engineering approach different solutions have been proposed and evaluated for the PFCs cooling system integration and for cassette fixation.

The selection of the preferred solution have been performed during decision-making stage taking into account several evaluation criteria and basing on the experts' opinions arisen during the annual Divertor Design Review Meeting [8].

The cooling layout option 2 presented in Section 3 has been selected for further developed in the next activities and it will be assumed as reference for interaction with other WPs. As regard the cassette fixation system, the ITER-like solution has been adopted for next activities and more optimization studies are ongoing in collaboration with WPRM.

Cassette parametric shell model developed allows to easily manage design changes and optimization iterative analyses. This model will be used for the next analyses tasks and cassettes' s ribs layout and thickness will be further optimized considering preloading needs, structural and neutron shielding issues. In addition, next design stages provides the integration of the selected solutions with the interfacing in-vessel components.

Acknowledgments

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