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

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HIGHLIGHTS

- Pre-conceptual design of DEMO divertor cassette is proposed in the paper.
- Divertor geometry has been developed taking into account the cooling parameters of the cassette Eurofer steel.
- Three options for PFCs cooling integration are proposed and discussed.
- Conceptual solutions for cassette fixation are proposed.
- A divertor cassette geometry is proposed as reference for future development.

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ABSTRACT

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, a systematic design method, the Iterative and Participative Axiomatic Design Process (IPADeP), has been adopted. Basing on Axiomatic Design, IPADeP supports the early conceptual design of complex systems. 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.

1. Introduction

One of the most relevant challenges in the development of next generation fusion reactors is the power exhaust and transmission from in-vessel components. The divertor cooling system design is important development in this regard. Since 2014 pre-conceptual design activities of the 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 (SE) 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). Pre-conceptual and conceptual design stages are characterized by a number of design iteration cycles, due to the high level of the

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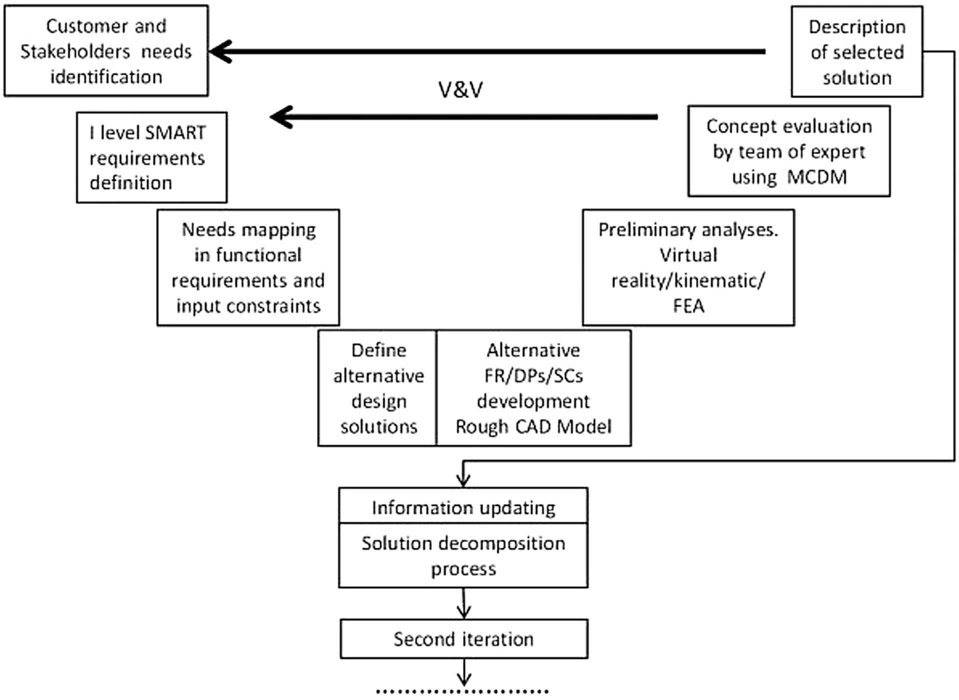

Fig. 1. IPADeP. FR: Functional Requirements, DP: Design Parameters, SC: System Components, MCDM: Multi Criteria Decision Making.

requirements during these stages and the continuous change of interfaces and technical requirements. The use of the systems engineering principles supported by the use of specific design methods allows for a systematic approach to design since the early phase of product development process. This helps to minimizing the risk related to the selection and development of wrong solution during the first phases. Fig. 1 shows a schematic view of the Iterative and Participative Axiomatic Design Process (IPADeP). Consistently with SE principles, it uses the principles of the Axiomatic Product Development Lifecycle (APDL) to provide a systematic process to deal with the first stages of the design. Detailed description of the process is available in [2,3].

IPADeP drives the design activities in the conceptual design stage, defining the requirements definition process and allowing for design activities documentation. The use of design matrix optimizes the traceability of requirements and design parameters, giving the opportunity to the design team to easily evaluate the impact of requirements change on system components, avoiding re-design cycles. IPADeP tools help in optimizing the collaboration among the parties involved in complex interdisciplinary projects and in minimizing the risks related to the uncertainty and incompleteness of requirements. Since conceptual stage is characterized by fuzzy and incomplete information, making the design process quite difficult and challenging, IPADeP proposes an iterative process focused on the experience of the people involved and deals with the decision making phase using a multicriteria decision making technique (MCDM).

In this paper the pre-conceptual divertor design activities are described, developed according to the first iteration line of IPADeP methodology. The work moved from the geometrical and interface constraints imposed by the 2015 DEMO configuration model (Fig. 2). Since different materials will be used for cassette (Eurofer) and PFCs (Cu-alloy) different coolant temperatures are required and hence two separate cooling loops are integrated into each cassette [3]. According to SE 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. The aim is to discuss the different proposed solutions and to highlight the main points arisen in the decision-making stage to support the further development of DEMO divertor.

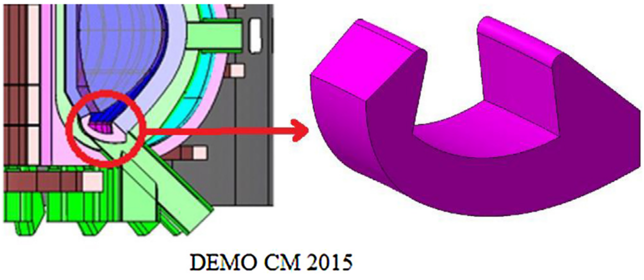

Fig. 2. 2015 DEMO Configuration Model.

Table 1
Cassette cooling parameters.

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

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 [4])
- Integration of PFCs cooling system
- Need to preload cassette to ensure electrical connection
- Eurofer technological limit: 40 mm maximum thick plates

The cassette surface model (Fig. 3a) has been developed in CATIA V5 surface environment using a parametric approach, in order to

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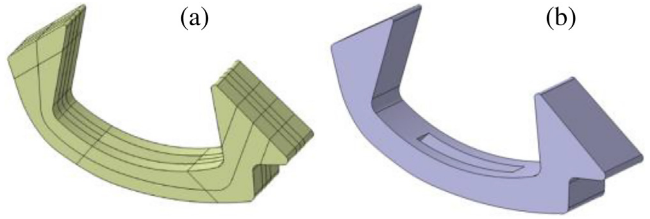

Fig. 3. (a) Cassette surface model, (b) solid model.

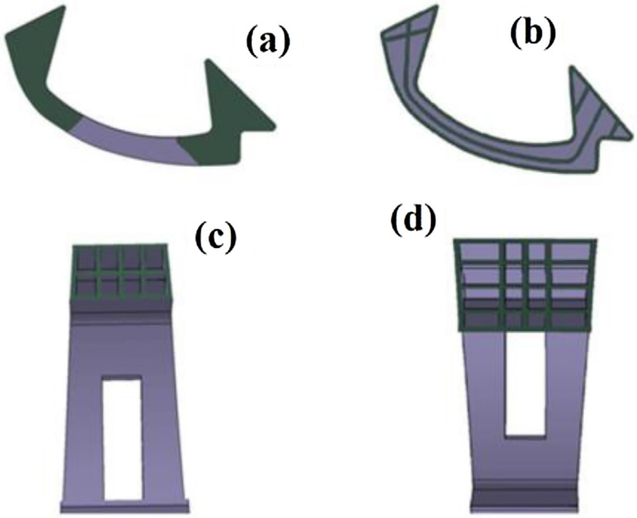

Fig. 4. Cassette body sections.

allow easy change of ribs position and thickness during analyses optimization process [5]. From this, the solid model (Fig. 3b) has been derived, directly linked to the surface one.

The cassette body is composed of an upper plate, a lower plate, side plates and internal toroidal and poloidal ribs (Figs. 4 and 5). The coolant enters and exits the cassette on the outboard through two inlet/outlet pipes passing through lower port. Fig. 5b shows the coolant path along radial direction.

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 thermo-hydraulic analyses, cooling parameters and preloading needs.

In interaction with Work Package Remote Maintenance (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.

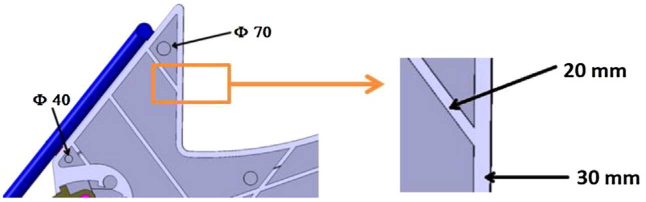

Fig. 6. Ribs thickness and holes diameters.

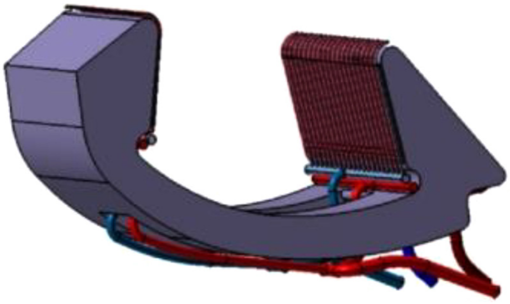

Fig. 7. First cooling configuration option: inlet and outlet manifolds are both located below targets.

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 issues in the design process, as well as the interfaces between feeding pipes and fixation systems. Mainly 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 duct in the cassette body and the presence of two manifolds on the bottom side for both inner and outer vertical target, for a total of four manifolds. Each manifolds distributes the coolant uniformly to the parallel cooling pipes of the target plate.

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.

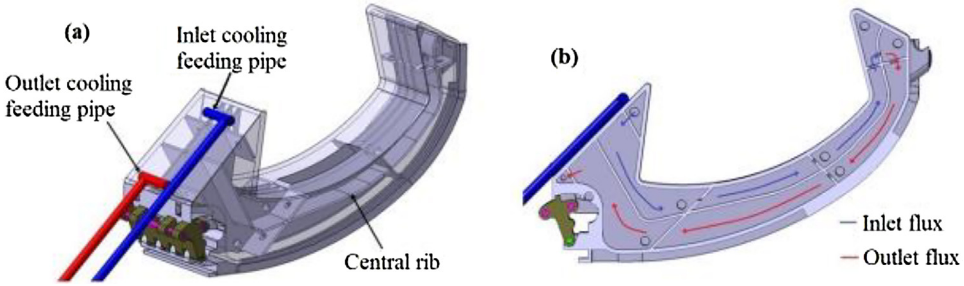

Fig. 5. (a) Internal cassette structure, (b) path followed by the coolant, the central poloidal rib separates the inlet and outlet fluxes inside the cassette.

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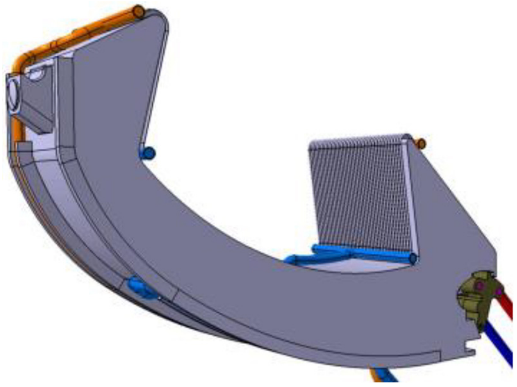


Fig. 8. Second configuration option.

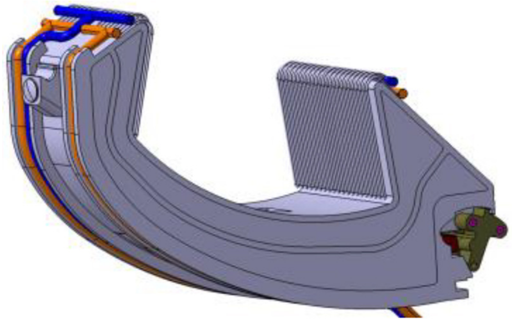


Fig. 9. Third configuration option.

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". Instead, they are located on the top and on the bottom of the vertical target, respectively.

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

Advantages

- Improved cooling of target PFC units (no U-turns in target cooling pipes).
- The cooling temperature at the strike point is lower than in the other two options improving the resistance against Critical Heat flux.

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.

Advantages

- Manifolds are well shielded by the blanket.

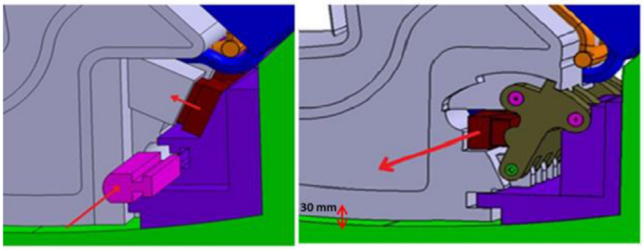
Disadvantages

- Interfaces with blanket, supporting system and RH tools.

Table 2
AHP results for cooling layout options.

Evaluation Criteria	Options	Score
Pipes protection	Option 1	0.25
Remote handling compatibility		
Maintenance time	Option 2	0.47
Heat flux performances		
Manufacturing feasibility	Option 3	0.33

According to IPADeP methodology, the three options have been pair-wise compared by a team of experts using the Analytic Hierarchy Process (AHP) technique [6]. The results showed that cooling layout option 2 is the most promising (Table 2), especially thanks to its expected best performances against the Critical Heat Flux.



(a) (b)

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

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 [4]. According to the systematic design process presented in [2], authors, in close interaction with the WPRM team, improve the fixation design solutions presented in [3,7] according to updated requirements and interfaces. 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 by 30 mm to close the gaps between blanket and the cassette. Two fixation options have been proposed and evaluated (Fig. 10).

The option 1 (Fig. 10a) provides cassette preloading to allow clearance removal and ensure electrical connection. After cassette preloading a mechanical component acting like a key is inserted toroidally between cassette and rail, to take fixed the cassette in the preloaded position. Such a component presents a spherical surface to allow for an easier insertion. Cassette interfaces and rail are properly formed to withstand loads in any direction. The second option (Fig. 10b) is essentially a simplified version of the

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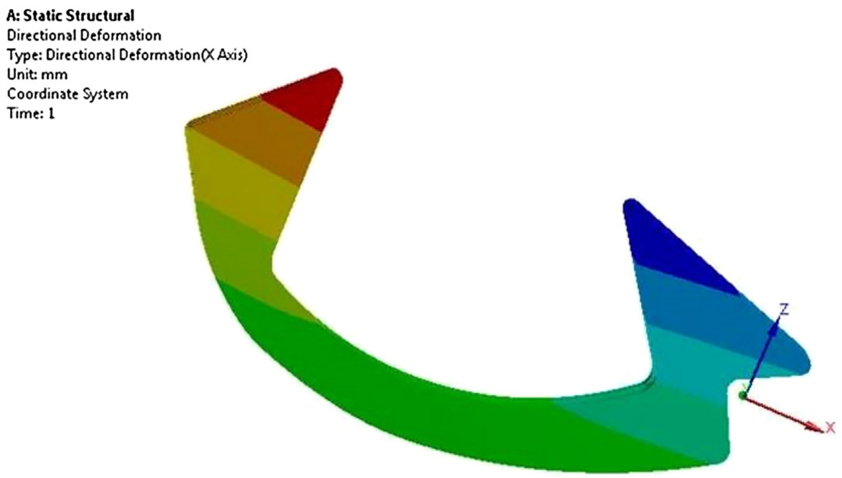

Fig. 11. First evaluation on preloading displacements.

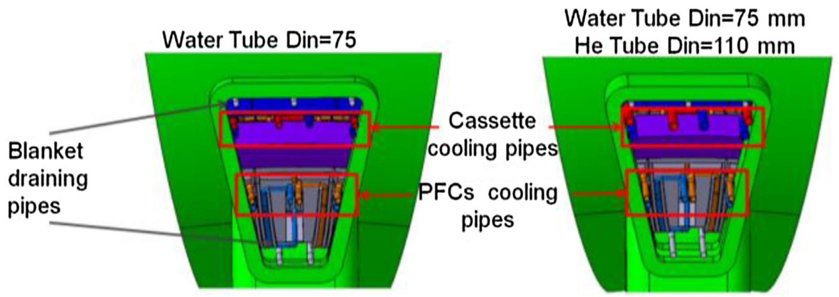

Fig. 12. Pipes integration at lower port.

ITER knuckle [8]. After cassette preloading and knuckle rotation, two pins are inserted by a robotic arm from the port to lock the left and right cassette. Cassette preloading is achieved in both the option proposed by an ITER-like hydraulic jack. A structural analysis has been performed assuming a preloading force of 100 kN (ITER-like preloading). The result is a displacement of 0.7 mm along the preloading direction (the line passing through outboard fixation system and the centre of the nose; Fig. 11).

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

According to IPADeP, the fixation systems have been pair-wise compared, by a team of experts including WPDIV and WPRM members. Option 2 (ITER-like) resulted as preferred option to be further developed. However design teams agreed that some possible backup options should be still taken in consideration.

Evaluation Criteria	Options	Score
Complexity Geometric Envelope RH compatibility Maintainability Inspectability	Option 1	0.33
	Option 2	0.4

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.

Since cassette and PFCs are cooled separately, four pipes are required for each cassette (two for PFCs cooling and two for cassette cooling). Hence, a total of 12 divertor cooling pipes pass through each lower port (three cassettes for each sector). In addition, blanket draining pipes pass through the lower port in the configuration model. The assessment has been carried out considering two distinct divertor pipes, corresponding on two cassette cooling options (Fig. 12): water cooled cassette ($D_{in} = 75$ mm) and helium cooled cassette ($D_{in} = 75$ mm for water pipes and $D_{in} = 110$ mm for helium pipes). Furthermore, integration with Helium and water-cooled blanket pipes at lower port is ongoing, showing critical interface issues to be fixed

6. Conclusions

The pre-conceptual design of the 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.

Following IPADeP, the selection of the preferred solutions have been performed during decision-making stage by means of AHP, involving team of experts. This allowed us to consider important design issue and integration aspects from the early stage of the design, providing the basis for avoiding re-design cycles due to requirements refinement and updating.

The cooling layout option 2 presented in Section 3 has been selected for further development 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 the cassette's rib layout and thickness will be further optimized considering preload-

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ing needs, structural and neutron shielding issues. The integration interfacing in-vessel components is also planned.

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