EUROFUSION WPDIV-CP(16) 15608

P.A. Di Maio et al.

Analysis of the steady state thermal-hydraulic behaviour of the DEMO Divertor cassette body cooling circuit

Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

Analysis of steady state thermal-hydraulic behaviour of the DEMO Divertor cassette body cooling circuit

P. A. Di Maio[a], S. Garitta[a], J. You[b], G. Mazzone[c], E. Vallone[a*]

[a]*University of Palermo, Viale delle Scienze, Edificio 6, 90128 Palermo, ITALY*
[b]*Max Planck Institute of Plasma Physics (E2M), Boltzmann Str.2, 85748 Garching, GERMANY*
[c]*ENEA C.R. Frascati, Via E. Fermi 45, 00044 Frascati (RM), ITALY*

In the framework of the work package “Divertor” of the EUROfusion action, a research campaign has been jointly carried out for the subproject “Cassette design and integration” by ENEA and University of Palermo to investigate the thermal-hydraulic performances of the DEMO divertor cassette body cooling system. A comparative evaluation study has been performed considering the two different options of divertor cassette body coolant, namely pressurized water and helium.

The research activity has been carried out following a theoretical-computational approach based on the finite volume method and adopting a qualified Computational Fluid-Dynamic (CFD) code.

CFD analyses have been carried out for the considered options of cassette body cooling circuit under nominal steady state conditions and their thermal-hydraulic performances have been assessed in terms of overall coolant thermal rise, coolant total pressure drop, flow velocity and pumping power, to check whether they comply with the corresponding limits.

Results obtained are reported and critically discussed.

Keywords: Divertor, cassette body, CFD analysis, hydraulics.

1. Introduction

The recent European Fusion Development Agreement roadmap was elaborated to pursue fusion as a sustainable, secure and commercial energy source [1]. In this framework, the divertor is a fundamental component of fusion power plants, being primarily responsible for power exhaust and impurity removal via guided plasma.

The divertor of 2015 DEMO design is composed of 54 toroidal cassettes, each articulated in a Cassette Body (CB) that supports two target plate Plasma Facing Components (PFCs): an Inner Vertical Target (IVT) and an Outer Vertical Target (OVT) (fig. 1) [2].

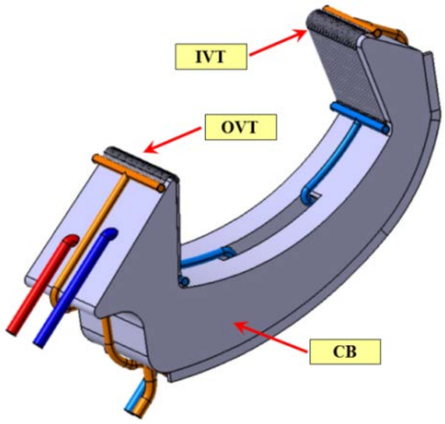

Fig. 1. 2015 DEMO divertor cassette.

Due to its position and functions, the divertor has to sustain very high heat and particle fluxes arising from the plasma (up to 20 MW/m^2), while experiencing an intense nuclear deposited power, which could jeopardize its structure and limit its lifetime. Therefore, attention has to be paid to the thermal-hydraulic design of its cooling system, in order to ensure a uniform and proper cooling, without an unduly high pressure drop.

Within the framework of the activities foreseen by the WP-DIV 1 “Divertor Cassette Design and Integration” of the EUROfusion action, a research campaign has been carried out at the University of Palermo, in cooperation with ENEA, to investigate the steady state thermal-hydraulic performances of the divertor Cassette Body cooling system. The assumptions are herein reported and critically discussed, together with the main results obtained.

A theoretical-numerical approach based on the Finite Volume Method has been followed adopting the commercial Computational Fluid-Dynamic (CFD) code ANSYS CFX.

2. Cassette body thermal-hydraulic analyses

Table 1 illustrates the main characteristics of the CB different cooling options currently under consideration, that differ in coolant, pressurized water for WCDCs (Water Cooled Divertor Cassette) and helium for HCDCs (Helium Cooled Divertor cassette), as well as in operative parameters. As far as nuclear heating data are concerned, they have been drawn from [3], while the information about average heat capacities and mass flow rates have been assessed by preliminary thermal-hydraulic calculations.

Attention has been specifically focused on cooling options HCDC+B4C and WCDC1, respectively a helium-cooled and a water-cooled CB design option.

---

author’s email: eugenio.vallone@unipa.it

Table 1. Summary of the CB cooling options features.

	WCDC1	WCDC2	HCDC	HCDC +B4C
Power [MW]	96	96	47	56
Power per cassette [MW]	1.778	1.778	0.870	1.037
Inlet pressure [MPa]	3.5	15.5	4.0	4.0
T_{in} [°C]	150	285	350	350
T_{out} [°C]	220	325	500	500
ΔT [°C]	70	40	150	150
$<c_p>$ [J/kg °C]	4451	5782	5195	5195
G [kg/s]	5.71	7.69	1.12	1.33

CFD analyses have been carried out to investigate the thermal-hydraulic performances in terms of:

- coolant flow velocity distribution;
- coolant overall pressure drop;
- coolant temperature distribution;
- CB structure temperature distribution.

Moreover, for each cooling option two CB design concepts have been studied, namely Cassette Body Design Concept I (CB-DCI) and II (CB-DCII). Since some criticalities have risen from the analyses of the original CB (the CB-DCI), in fact, a lay-out revision has been proposed, differing in flow paths and in structure thickness, and CB-DCII has been realised. Table 2 and 3 summarise mesh parameters and main assumptions adopted. Fig. 2 shows a detail of the typical mesh set-up.

Table 2. Summary of the main mesh parameters.

Region	Mesh Parameter	CB-DCI	CB-DCII
Fluid	**Nodes**	$8.06\cdot10^{+6}$	$9.42\cdot10^{+6}$
	Elements	$2.02\cdot10^{+7}$	$2.38\cdot10^{+7}$
	First layer thickness [μm]	200	200
	Inflation layers number	12	12
	Layers growth rate	1.4	1.4
Structure	**Nodes**	$4.79\cdot10^{+6}$	$4.73\cdot10^{+6}$
	Elements	$2.39\cdot10^{+7}$	$2.39\cdot10^{+7}$

Table 3. Summary of the CFD analyses set-up parameters.

	HCDC+B4C	WCDC1
Analysis type	Steady state	Steady state
Material library	He ideal gas	IAPWS IF97
Flow inlet temperature	350°C	150°C
Turbulence model	k-ε	k-ε
Boundary layer modelling	Scalable wall functions	Scalable wall functions
Wall roughness	15 μm	15 μm
Inlet BC	$p_s = 4.0$ MPa	$p_s = 3.5$ MPa
Outlet BC	G = 1.33 kg/s	G = 5.71 kg/s

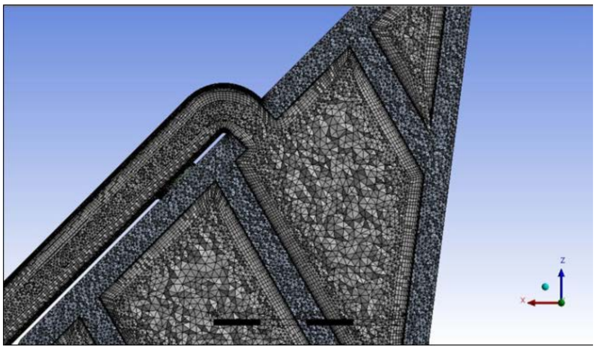

Fig. 2. Detail of a typical mesh set-up.

2. CB-DCI CFD analyses results

Fig. 3 illustrates a 3-D rendering of the analysed fluid and structure domain relevant to Cassette Body Design Concept I (CB-DCI).

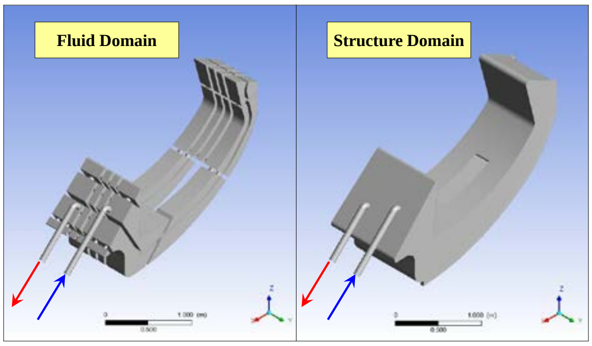

Fig. 3. CB-DCI fluid and structure domain.

Steady state CDF analyses have been carried out for both the HCDC+B4C and WCDC1 options and they have allowed to appreciate some issues with the CB-DCI, mainly relevant to the assessed temperature field. In fact, there is a safety limit (550 °C) in the temperature of the CB structure, realised in EUROFER, that should not be overcome [4]. Furthermore, in the water-cooled option the fluid should not reach the saturation point, in order to allow a subcooled flow in each part of the domain.

Fig. 4 and 5 are relevant to the helium-cooled option and show respectively part of the fluid velocity field inside the CB and details of the structure temperature field. In particular, fig. 5 shows that there are wide critical areas where the temperature is above the limit of 550 °C.

Fig. 6 refers to the WCDC1 and shows the coolant critical areas, conservatively defined as the regions where water temperature is above the saturation temperature at the minimum pressure reached inside the flow domain. Fig. 7 refers to the water-cooled option as well and highlights structure critical areas (T>550 °C).

Finally, table 4 summarizes the main results obtained for these CDF calculations, additionally showing that there are more than three orders of magnitude between helium coolant and water coolant calculated pumping power.

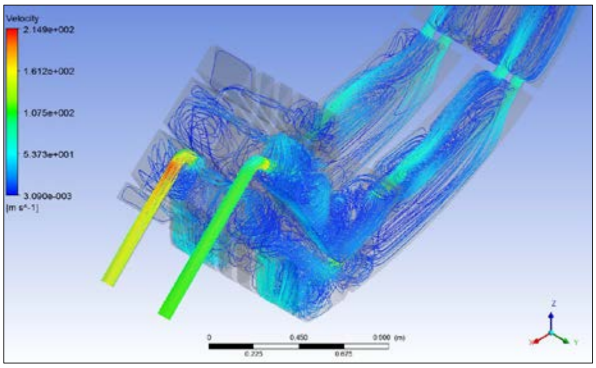

Fig. 4. CB-DCI: HCDC+B4C fluid velocity field.

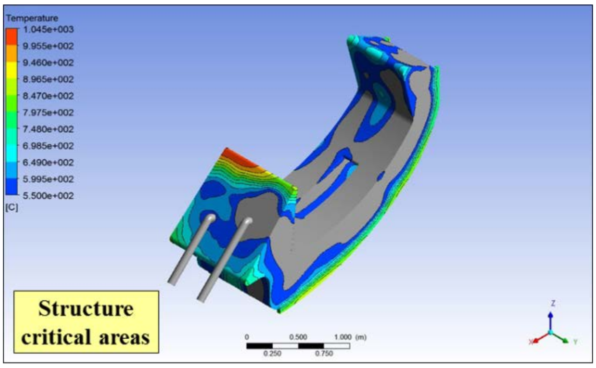

Fig. 5. CB-DCI: HCDC+B4C structure temperature field.

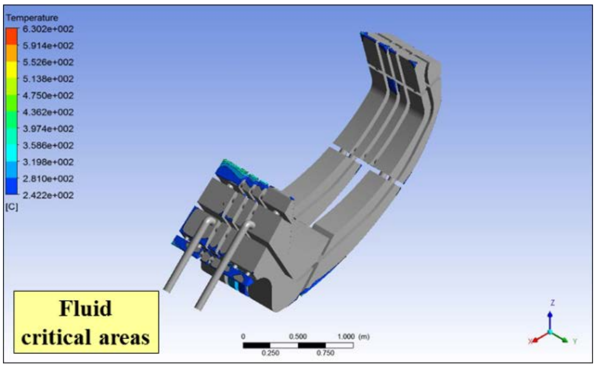

Fig. 6. CB-DCI: WCDC1 fluid temperature field.

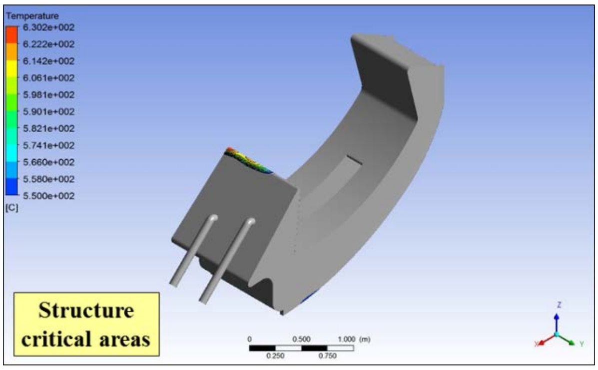

Fig. 7. CB-DCI: WCDC1 structure temperature field.

Table 4. CB-DCI CFD analyses main results.

	HCDC+B4C	**WCDC1**
Δp [MPa]	0.1809	0.0096
Pumping power [kW]	78.547	0.058
ΔT [°C]	153.6	70.9
Fluid T_{max} [°C]	704.2	293.3
Structure T_{max} [°C]	1045.4	630.2

3. Cassette body design concept II CFD analyses

In order to improve the thermal-hydraulic performances of CB-DCI, the Cassette Body Design Concept II (CB-DCII) has been devised. Specifically, the position of inlet/outlet manifolds attachment has been changed (fig. 8) and the thickness of the structure and of its internal ribs has been decreased of a factor 1.3÷2, along with a modification of the corners under IVT and OVT (fig. 9). Those alterations have aimed to improve flow uniformity and, in general, to enhance the cassette cooling effectiveness.

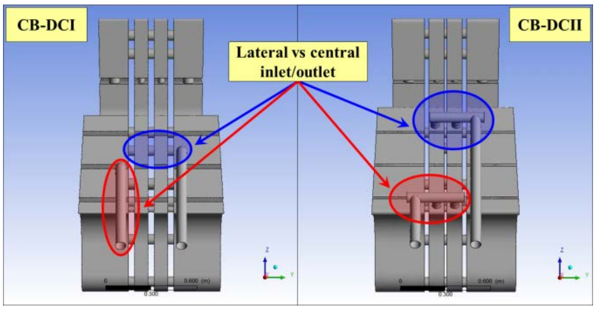

Fig. 8. CB-DCI and CB-DCII manifolds attachment.

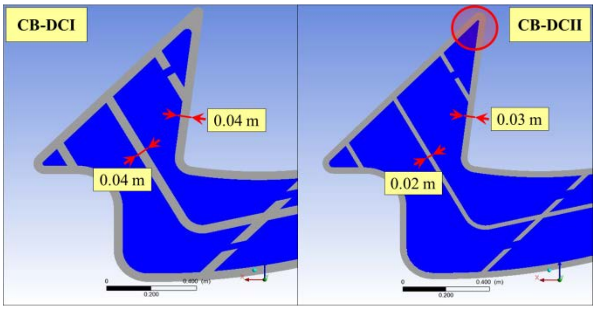

Fig. 9. CB-DCI and CB-DCII structure differences.

In analogy with the previous cases, steady state CDF analyses have been carried out for the HCDC+B4C and the WCDC1 option.

Results obtained have shown that, as it was forecast, temperature fields globally assess at lower values. EUROFER maximum temperature (550°C) is overcome in large areas of CB structure only for HCDC+B4C (fig. 10). Furthermore, only extremely localized coolant vaporization is predicted in water configuration (fig. 11). Table 5 summarizes the main results, additionally showing limited changes in the evaluated pressure drops and pumping power.

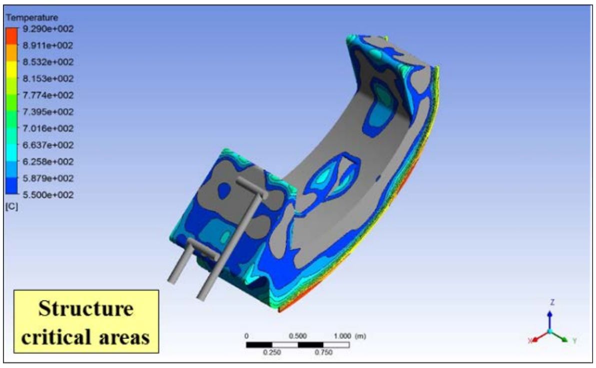

Fig. 10. CB-DCII: HCDC+B4C structure temperature field.

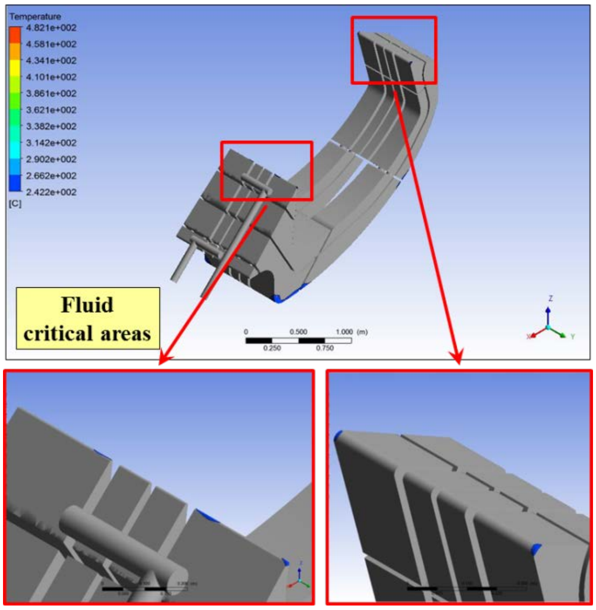

Fig. 11. CB-DCII: WCDC1 fluid temperature field.

Table 5. CB-DCII CFD analyses main results.

	HCDC+B4C	**WCDC1**
Δp [MPa]	0.2108	0.0122
Pumping power [kW]	92.068	0.076
ΔT [°C]	149.1	70.3
Fluid T_{max} [°C]	610.2	242.4
Structure T_{max} [°C]	929.0	482.1

4. Conclusions

Within the framework of the activities foreseen by the WP-DIV 1 of the EUROfusion action, a research campaign has been carried out at the University of Palermo, in cooperation with ENEA, to investigate the steady state thermal-hydraulic performances of the divertor Cassette Body cooling system. Specifically, two different options have been studied, namely Cassette Body Design Concept (CB-DC) I and II, and in both cases a helium-cooled (HCDC+B4C) and a water-cooled (WCDC1) configuration has been considered.

Results obtained for the CB-DCI analyses have indicated that a lay-out revision should be implemented, since its behaviour do not fully comply with safety and operative limits. In particular, structural material always overcomes its maximum temperature (550°C), no matter of the adopted coolant. Moreover, water coolant experiences vaporizations in wide CB regions. Finally, the flow path needs to be improved as to guarantee a more effective cooling, particularly to the outboard CB corners.

As far as CB-DCII option is concerned, structure and flow paths have been revised. As a consequence, structural material overcomes its maximum temperature only in case of helium coolant. In addition, water coolant does not experience significant vaporization. Finally, pressure drops predicted for this concept are slightly higher than those of CB-DCI, no matter of coolant.

In conclusion, from the thermal-hydraulic standpoint, Cassette Body Design Concept II seems to be more effective than the Concept I.

As to the calculated pumping power, for both the concepts in case of helium coolant it roughly amounts to ≈1300 times that relevant to the use of water coolant. In particular, total pumping power for all the 54 Cassettes ranges between 4.24 MW and 4.97 MW in case of helium and between 3.1 and 4.1 kW in case of water.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] F. Romanelli et alii, Fusion Electricity - A Roadmap to the Realisation of Fusion Energy, European Fusion Development Agreement (EFDA), 2012, ISBN 978-3-00-040720-8T.

[2] Final Report on Deliverable DEMO Divertor - Thermo-hydraulic assessment report 2015, Report IDM reference No EFDA_D_2MY45W, DIV-1-T001-D010.

[3] S. Villari et alii, DR-DIV-01-2-Structural feasibility of cassette body material, EFDA_D_2N2F23 v1.2

[4] EUROfusion, personal communications.