WPDIV-CPR(18) 20207

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Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

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.

Hydraulic analysis of EU-DEMO divertor plasma facing components cooling circuit under nominal operating scenarios

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Within the framework of the Work Package DIV 1 - "Divertor Cassette Design and Integration" of the EUROfusion action, a research campaign has been jointly carried out by University of Palermo and ENEA to investigate the steady state thermal-hydraulic behaviour of the DEMO divertor cassette cooling system, focussing the attention on its Plasma Facing Components (PFCs). The research campaign has been carried out following a theoretical-computational approach based on the Finite Volume Method and adopting the commercial Computational Fluid-Dynamic code ANSYS-CFX.

A realistic model of the PFCs cooling circuit has been analysed, specifically embedding each Plasma Facing Unit (PFU) cooling channel with the foreseen swirl tape turbulence promoter, hence resulting in a finite volume model much more detailed than those assessed in previous analyses. Its thermal-hydraulic performances have been numerically evaluated under nominal steady state conditions, also comparing the obtained results with the corresponding outcomes of analogous analyses carried out for a simplified PFCs configuration, without swirl tapes. Moreover, the main thermal-hydraulic parameters have been evaluated in order to check whether the considered PFCs cooling circuit might fulfil the total pressure drop requirement ($\Delta p < 1.4$ MPa), providing a uniform cooling of the Vertical Target PFU channels with a viable CHF margin (> 1.4).

The PFCs cooling circuit thermal-hydraulic behaviour has been additionally assessed at alternative operative conditions, issued to check the viability of a coolant velocity reduction, in order to minimize corrosion and vibrations inside the PFU channels.

Models, loads and boundary conditions assumed for the analyses are herewith reported and critically discussed, together with the main results obtained.

Keywords: DEMO, divertor, plasma facing components, CFD analysis, thermofluid-dynamics.

1. Introduction

Within the framework of the activities foreseen by the WP-DIV 1 - "Divertor Cassette Design and Integration" [1] of the EUROfusion action, a research campaign has been jointly carried out by University of Palermo and ENEA to investigate the steady state thermal-hydraulic behaviour of the DEMO divertor Plasma Facing Components (PFCs) cooling system [2,3].

In particular, a realistic model of the PFCs cooling circuit has been developed. Its thermal-hydraulic performances have been numerically evaluated under nominal steady state reference and alternative conditions, the latter being issued to check the viability of a coolant velocity reduction, in order to minimize corrosion and vibrations inside the Plasma Facing Unit (PFU) channels. Moreover, the main thermal-hydraulic parameters have been evaluated in order to check whether the considered PFCs cooling circuit might fulfil the total pressure drop requirement ($\Delta p < 1.4$ MPa), providing a uniform cooling of the vertical target PFU channels with a viable CHF margin (> 1.4).

The research campaign has been carried out following a theoretical-computational approach based on the finite volume method and adopting the commercial Computational Fluid-Dynamic (CFD) code ANSYS CFX v.16.2, employed also to evaluate concentrated hydraulic resistances to be used in system codes [4,5,6].

Analysis models and assumptions are herein reported and critically discussed, together with the main results obtained.

2. Outline of DEMO divertor cassette

According to its 2016 design, DEMO divertor is articulated in 54 toroidal cassettes, each composed of a Cassette Body (CB) supporting two PFCs, namely an Inner Vertical Target (IVT) and an Outer Vertical Target (OVT) (Fig. 1), composed of actively cooled PFUs equipped with a Swirl Tape (ST) turbulence promoter.

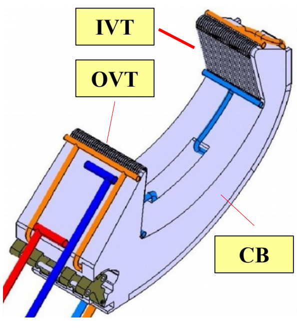

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Fig. 1. DEMO divertor cassette 2016 design.

3. PFCs cooling circuit

The analysed PFCs cooling circuit has been issued during the second half of 2016 [7]. In particular, it is characterised by 31 PFU channels in the IVT and 39 in the OVT and by two separate OVT outlet manifolds. Moreover, it differs from the original 2016 configuration for the manifolds diameter (increased by a factor 1.4) and for the presence of a properly-shaped diffuser between VTs manifolds and their inlet headers.

The realistic configuration embedded with swirl tape turbulence promoters inside each PFU cooling channel has been considered for 2017 analyses (Fig. 2).

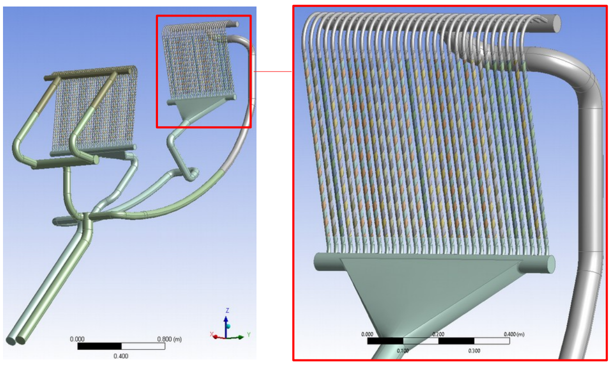

Fig. 2. PFCs cooling circuit analysed during 2017.

It relies on the use of subcooled pressurized water at the inlet pressure and temperature of 5 MPa and 130 °C, respectively, flowing under quasi-isothermal conditions.

4. PFCs cooling circuit CFD analysis

Initially, the thermal-hydraulic behaviour of this PFCs cooling circuit layout option has been assessed assuming the reference coolant operative conditions agreed in October 2016 with EUROfusion teams. Later on, the so-called "alternative" operating conditions have been considered. These conditions have been obtained from the former ones with the aim to reduce corrosion inside the PFU channels. As a consequence, also the inlet temperature has been decreased, so to allow the new CHF margin distribution to fulfil the prescribed requirement, and its value has been set to 90 °C. The two considered coolant operative conditions are summarised in Table 1.

Table 1. Summary of coolant operative conditions.

	Reference conditions	Alternative Conditions
Inlet Pressure [MPa]	5.0	5.0
Inlet Temperature [°C]	130	90
ΔT [°C]	6	9
Removed Power [MW]	136	136
G per Cassette [kg/s]	98.63	67.56

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The thermal-hydraulic performances of the PFCs cooling circuit under coolant operative conditions of Table 1 have been assessed by running steady state, isothermal CFD analyses. Selected mesh parameters and main assumptions, models and Boundary Conditions (BCs) adopted are reported in Tables 2 and 3, respectively.

Table 2. Summary of selected mesh parameters.

Nodes	$6.305 \cdot 10^{+7}$
Elements	$8.035 \cdot 10^{+7}$
Inflation layers number	12
First layer thickness [μm]	12
Layers growth rate	1.4
Typical element size [m]	$2.18 \cdot 10^{-3}$
Min/Avg/Max y^+	2.972/112.3/496.3

Table 3. Summary of assumptions, models and BCs.

	Reference conditions	Alternative Conditions
Analysis type	Steady state	Steady state
Material library	IAPWS IF97	IAPWS IF97
Temperature	133 °C	95 °C
Turbulence model	k-ε	k-ε
Boundary layer modelling	Scalable wall functions	Scalable wall functions
Wall roughness	2 μm	2 μm
Inlet BC (Static pressure)	5 MPa	5 MPa
Outlet BC (Mass flow rate)	98.63 kg/s	67.56 kg/s

5. Results at Reference Operative Conditions

The coolant total pressure spatial distribution among the PFCs cooling circuit assessed at the reference operative conditions is reported in Fig. 3, while total pressure drops across the main sections of the circuit are reported in Table 4. The PFCs cooling circuit overall total pressure drop amounts to ~1.1 MPa, resulting lower than the prescribed limit of 1.4 MPa.

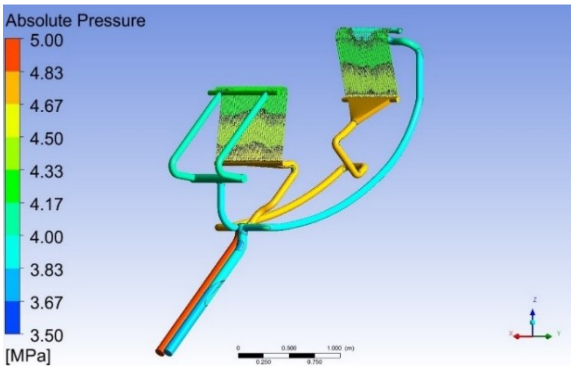

Fig. 3. PFCs coolant total pressure field (reference conditions).

Table 4. PFCs cooling circuit total pressure drop distribution (reference conditions).

Sections	Δp [MPa]
Inlet Common Manifold	0.0131
IVT	0.6855
OVT	0.6424
IVT/OVT total	1.0444
Outlet Common Manifold	0.0315
TOTAL	1.0890

Moreover, attention has been paid also to the distributions of the coolant axial flow velocity (V_{ax}) among the PFU channels of both OVT and IVT. Coolant axial flow velocity distributions have been reported in Fig. 4 and key-parameters are shown in Table 5.

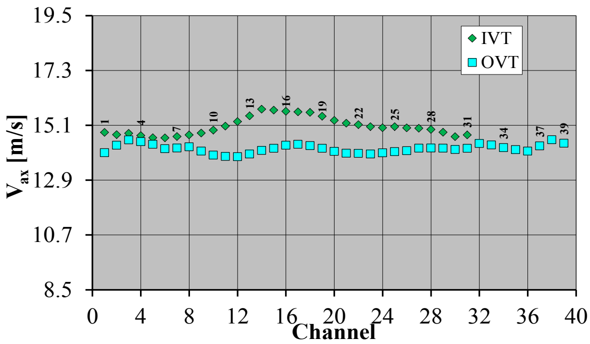

Fig. 4. Coolant axial flow velocity distribution among OVT PFU channels (reference conditions).

Table 5. Coolant axial flow velocity distribution key-parameters (reference conditions).

	OVT	IVT
Max V_{ax} [m/s]	14.517	15.746
Min V_{ax} [m/s]	13.837	14.595
$\varepsilon_{Max-Min}$	4.68%	7.31%
Average V_{ax} [m/s]	14.161	15.053
σ [m/s]	0.172	0.362

From the analysis of the results obtained, it may be argued that within the PFU channels of each one of the two investigated VTs the distribution of coolant axial flow velocity is quite uniform, since maximum deviations lower than 8% have been estimated between the maximum (Max V_{ax}) and minimum (Min V_{ax}) values.

The distributions of the margin against CHF onset within the VTs PFU cooling channels have been assessed for the PFCs cooling circuit, mainly in order to check whether its prescribed minimum value of 1.4 is guaranteed by the cooling circuit layout. To this purpose, attention has been paid to the strike point sections of both OVT and IVT, where it has been supposed to be located the peak value of the incident heat flux arising from plasma. In these sections, water coolant has been supposed to flow at the temperature of 133 °C, with the local values of total pressure and axial flow velocity previously calculated for each VTs PFU channel. In these hypotheses, the CHF at the interface between the coolant and the channel walls has been calculated for each VTs PFU channel by means of the proper correlation given in [8]. CHF margin distributions have been reported in Fig. 5, while key-parameters have been summarized in Table 6.

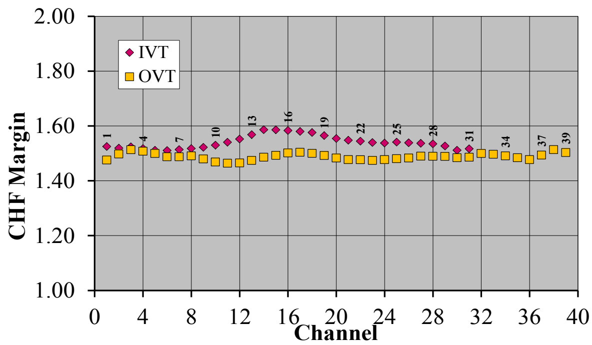

Fig. 5. CHF margin distribution among OVT PFU channels (reference conditions).

Table 6. CHF margin distribution key-parameters (reference conditions).

	OVT	IVT
Max CHF Margin	1.513	1.586
Min CHF Margin	1.464	1.510
$\varepsilon_{Max-Min}$	3.27%	4.80%
Average CHF Margin	1.488	1.540
σ	0.012	0.024

From the analysis of the results obtained, it may be argued that the calculated distributions of CHF margin are acceptably uniform for both the VTs, since deviations between their pertaining maximum and minimum values amount to less than 5%. Moreover, both minimum and average calculated values for both VTs PFU channels result higher than the minimum

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prescribed value of 1.4.

6. Results at Alternative Operative Conditions

The alternative conditions have been issued to check the viability of a coolant velocity reduction (to less than 12 m/s [9]) in order to minimize corrosion.

Moreover, the inlet temperature has been lowered to 90 °C, as it has been calculated to be, using the results of the previous analysis and by means of simple iterative analytical calculations, the minimum value that allow to keep the CHF margin distribution above the limit of 1.4.

Total pressure spatial distribution and total pressure drops distribution are reported in Fig. 6 and Table 7, respectively.

PFCs cooling circuit total pressure drop amounts to ~0.5 MPa, about half of the value calculated at reference conditions. Axial flow velocity distributions among PFU channels have been reported in Fig. 7, summarising the main parameters in Table 8.

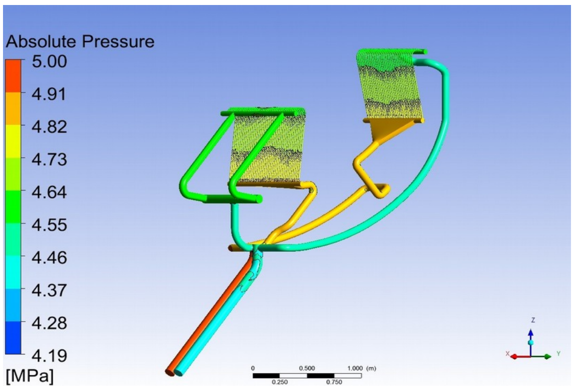

Fig. 6. PFCs coolant total pressure field (alternative conditions).

Table 7. PFCs cooling circuit total pressure drop distribution (alternative conditions).

Sections	Δp [MPa]
Inlet Common Manifold	0.0063
IVT	0.3231
OVT	0.2983
IVT/OVT total	0.4917
Outlet Common Manifold	0.0114
TOTAL	0.5093

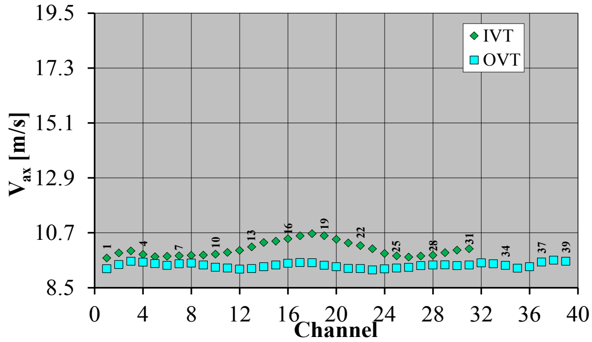

Fig. 7. Coolant axial flow velocity distribution among OVT PFU channels (alternative conditions).

Table 8. Coolant axial flow velocity distribution key-parameters (alternative conditions).

	OVT	IVT
Max V_{ax} [m/s]	9.599	10.663
Min V_{ax} [m/s]	9.212	9.689
$\varepsilon_{Max\text{-}Min}$	4.04%	9.14%
Average V_{ax} [m/s]	9.392	10.032
σ [m/s]	0.102	0.290

From the analysis of the results obtained, it may be argued that within each one of the two investigated VTs the distribution of coolant axial flow velocity among PFUs is quite uniform, since maximum deviations lower than 10% have been estimated between the maximum (Max V_{ax}) and minimum (Min V_{ax}) calculated values.

The distributions of the margin against CHF onset within the VTs PFU cooling channels have been assessed. In particular, the obtained CHF margins distributions have been reported in Fig. 8, while key-parameters have been summarized in Table 9.

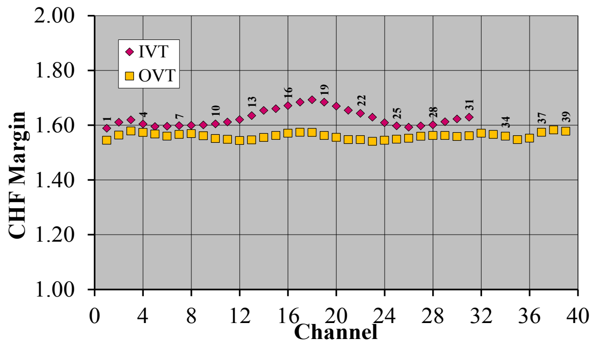

Fig. 8. CHF margin distribution among OVT PFU channels (alternative conditions).

Table 9. CHF margin distribution key-parameters (alternative conditions).

	OVT	IVT
Max CHF Margin	1.583	1.693
Min CHF Margin	1.541	1.588

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$\varepsilon_{Max-Min}$	2.64%	6.16%
Average CHF Margin	1.560	1.625
σ	0.011	0.031

From the analysis of the results obtained, it may be argued that the calculated distributions of CHF margin are acceptably uniform for both the VTs, since deviations between their pertaining maximum and minimum values amount to less than 6.5%. Moreover, both minimum and average values of CHF margin calculated for both VTs PFU channels result higher than the prescribed limit of 1.4.

7. Conclusions

Within the framework of the activities foreseen by the WP-DIV 1 "Divertor Cassette Design and Integration" of the EUROfusion action, during 2017 a research campaign has been carried out at the University of Palermo, in cooperation with ENEA, to theoretically investigate the steady state thermal-hydraulic performances of the DEMO divertor PFCs. To this purpose, a theoretical-computational approach based on the finite volume method has been followed and the commercial CFD code ANSYS-CFX has been adopted.

The PFCs cooling circuit steady state thermal-hydraulic performances have been numerically assessed in terms of coolant total pressure drop, flow velocity and CHF margin distributions, to check whether it comply with the corresponding reference limits. The CFD analysis of this PFCs configuration has shown that its cooling circuit complies with the prescribed requirements. In particular, it has shown a total pressure drop of 1.0890 MPa, widely lower than the limit of 1.4 MPa, and a minimum margin against CHF occurrence of 1.464, higher than the limit of 1.4. Moreover, this compliance has been also confirmed for the circuit operating at alternative conditions, issued to check the viability of a coolant velocity reduction in order to minimize corrosion inside the PFU channels.

Acknowledgments

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