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Thermal-hydraulic behaviour of the DEMO divertor plasma facing components cooling circuit

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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 cooling system. A comparative evaluation study has been performed considering three different options of cooling circuit layout for the divertor Plasma Facing Components (PFCs). The potential improvement in the thermal-hydraulic performance of the cooling system to be achieved by modifying the coolant circuit layouts has been also assessed and discussed in terms of optimization strategy.

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 PFCs cooling circuit lay-out options 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 Critical Heat Flux margin distributions along the vertical target Plasma Facing Unit channels, to check whether they comply with the corresponding limits.

Therefore, an optimisation study has been carried out to minimize the cooling options total pressure drop by properly changing their geometric configuration. In particular, the potential effect of increasing PFC inlet/outlet manifold diameter has been investigated with encouraging results for all the analysed options. Results obtained are reported and critically discussed.

Keywords: PFCs, CFD analysis, hydraulics.

1. Introduction

The recent European Fusion Development Agreement roadmap was drafted to realize commercially viable fusion power generation [1]. Within this framework, the divertor is a key in-vessel component, being responsible for power exhaust and impurity removal via guided plasma exhaust.

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

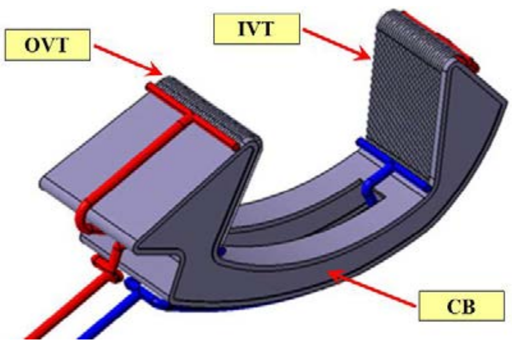

Fig. 1. 2015 DEMO divertor cassette.

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 to ensure a uniform and proper cooling, providing a safe margin against Critical Heat Flux (CHF) without an unduly high pressure drop.

In the framework of the activities foreseen by the WP-DIV 1 "Divertor Cassette Design and Integration" of the EUROfusion action [2], 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 DEMO divertor cassette cooling system, focusing the attention on the three different lay-out options currently under consideration for its PFCs cooling circuit (fig. 2) [2].

Three separate and independent analyses have been carried out under nominal conditions to evaluate their thermal-hydraulic performances. Specifically, overall coolant thermal rise, overall coolant pressure drop, flow velocity and CHF margin distributions along the PFU channels have been assessed, in order to check whether they comply with the corresponding reference limits, namely the maximum coolant total pressure drop (1.4 MPa), the minimum axial flow velocity along PFU channels (16 m/s) and the minimum margin against CHF onset (1.5) at the strike point sections of both IVT and OVT PFU channels.

Moreover, the assessment of potential lay-out

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modifications of the cooling options has been pursued as a pivotal goal too, allowing the improvement of their thermal-hydraulic performances. The assumptions are herein reported and critically discussed, together with the main results obtained.

The research campaign has been carried out following a theoretical-computational approach based on the Finite Volume Method, adopting the commercial Computational Fluid-Dynamic (CFD) code ANSYS CFX.

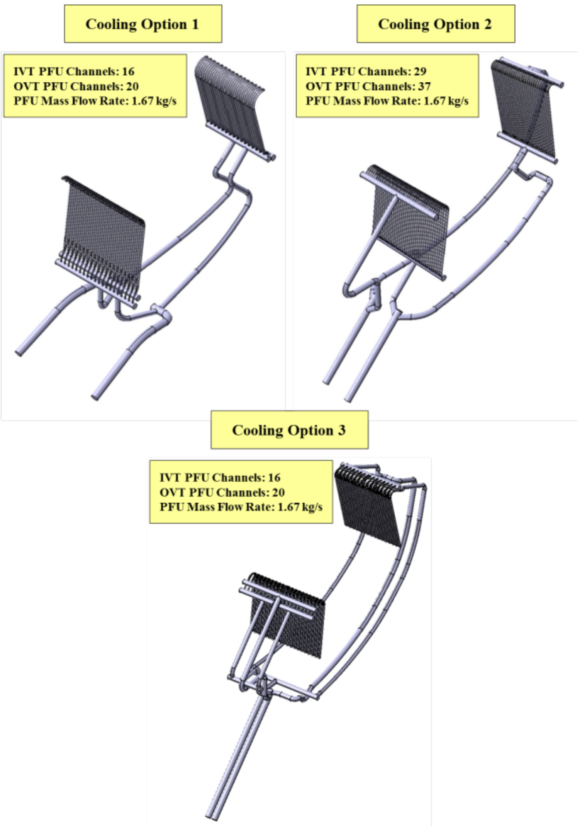

Fig. 2. DEMO divertor PFCs cooling systems.

2. Overall thermal rise calculation

In order to assess the thermal rise the coolant experiences under nominal conditions, it has been considered the fraction of the nuclear power deposited in the DEMO reactor that interests the PFCs (red boxes in power breakdown of fig. 3) [3].

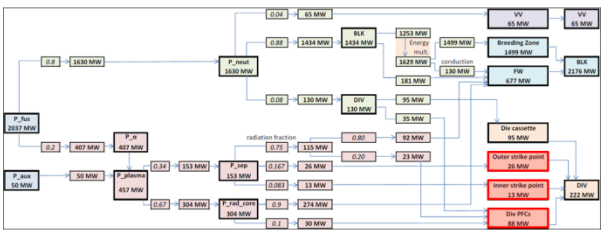

Fig. 3. DEMO nuclear deposited power breakdown.

It has also been assumed a steady state, "quasi" isobaric flow of pressurized sub-cooled water through the PFCs cooling circuits, along with a coolant reference mass flow rate along each single PFU cooling channel of 1.67 kg/s. This was a starting parameter and a follow-up study on the case with a reduced mass flow rate combined with decreased coolant temperature is currently ongoing [4]. Coolant thermal rises have been calculated for the three lay-out options (table 1), in particular hypothesizing water average thermodynamic state to be represented by that necessary to have a pressure of 5 MPa and a temperature of 150 °C at the Vertical Targets (VTs) strike points.

Table 1. Summary of coolant thermal rise calculations.

	Cooling Option 1	Cooling Option 2	Cooling Option 3
Total mass flow rate [kg/s]	60.1	110.2	60.1
ΔT [°C]	9.1	5.0	9.1

As it may be deduced from table 1, the calculated coolant thermal rises result to be modest, therefore allowing to assume isothermal flow conditions for the CFD analysis.

3. PFCs cooling circuit CFD analysis

The thermal-hydraulic performances of the three lay-out options of the DEMO divertor cassette PFCs cooling circuit have been investigated under nominal conditions by running separate, steady state, isothermal CFD analyses.

A summary of the selected mesh parameters and of the main assumptions, models and boundary conditions adopted is reported in tables 2 and 3.

Table 2. Summary of the main mesh parameters.

	Cooling Option 1	Cooling Option 2	Cooling Option 3
Nodes	$4.97 \cdot 10^{+6}$	$4.78 \cdot 10^{+6}$	$5.33 \cdot 10^{+6}$
Elements	$1.12 \cdot 10^{+7}$	$1.08 \cdot 10^{+7}$	$1.20 \cdot 10^{+7}$
Skewness	0.197	0.202	0.191
Inflation layers number	10	10	10
First layer thickness [μm]	20	20	20
Layers growth rate	1.41	1.41	1.41
Typical element size [m]	$3.08 \cdot 10^{-3}$	$3.48 \cdot 10^{-3}$	$3.60 \cdot 10^{-3}$
Model simplification	No swirl	No swirl	No swirl

Table 3. Summary of CFD analysis setup.

	Cooling Option 1	Cooling Option 2	Cooling Option 3
Material library	IAPWS IF97	IAPWS IF97	IAPWS IF97
Temperature	150 °C	150 °C	150 °C
Turbulence model	k-ε	k-ε	k-ε
Wall roughness	15 μm	15 μm	15 μm
Inlet BC	$p_s = 5$ MPa	$p_s = 5$ MPa	$p_s = 5$ MPa
Outlet BC	G = 60.1 kg/s	G = 110.2 kg/s	G = 60.1 kg/s

Fig. 4 shows a detail of the typical mesh set-up for each CFD analysis.

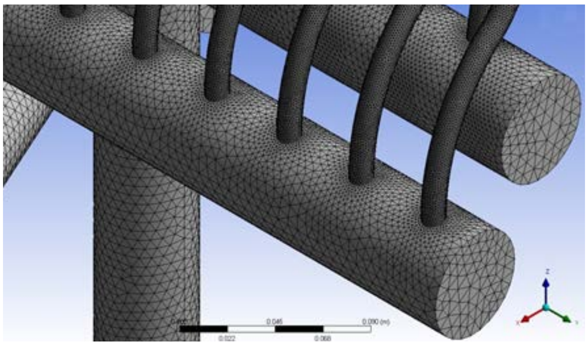

Fig. 4. Detail of a typical mesh set-up.

Section 3.1. shows the typical analysis results obtained for the first cooling option in an extensive way, while paragraph 3.2. summarizes the main results obtained for all the lay-out options under consideration.

3.1. PFCs Cooling Option 1 CFD analysis - Results

The pressure drops across the main sections of the Cooling Option 1 of the DEMO divertor cassette PFCs cooling circuit are reported in table 4.

Table 4. PFCs Cooling Option 1 total pressure drops.

Pressure points	Δp [MPa]
OVT segment	1.12
IVT segment	1.23
TOTAL	1.54

It has to be highlighted that the simplifying hypothesis that no swirl tapes are located inside the PFU cooling channels has been adopted. Therefore, a proper correction of the pressure drops has to be performed, otherwise they would result heavily underestimated. The effect of these turbulence promoters has been estimated according to [5] and [6], conservatively evaluating the additional pressure drop with reference to the highest predicted mass flow rate for VTs PFU cooling channels.

As a result, the circuit total pressure drop has to be roughly raised to $\Delta p=1.54+0.42=1.96$ MPa.

The VTs mass flow rates (table 5) and the coolant flow velocity field distribution have been assessed, mainly in order to check whether unbalanced distributions might take place within the circuit, preventing a uniform cooling of its solid components.

Table 5. Cooling Option 1 VTs mass flow rates.

	Calculated G [kg/s]	Nominal G [kg/s]	Deviation
OVT	32.7	33.4	-2.1%
IVT	27.4	26.7	2.6%

Furthermore, the coolant axial velocity distributions among the PFU channels of both OVT and IVT have been evaluated in presence of swirl tapes (fig. 5 and 6).

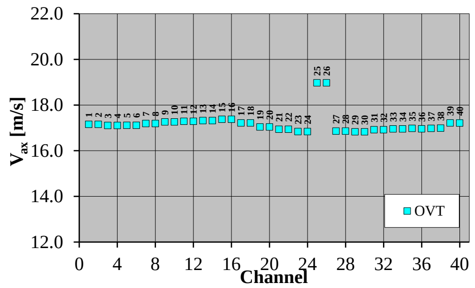

Fig. 5. Cooling Option 1 axial velocities along OVT PFUs.

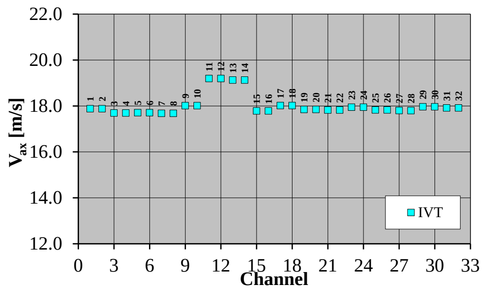

Fig. 6. Cooling Option 1 axial velocities along IVT PFUs.

The previous graphs show that, within the PFU channels, the distribution of axial flow velocity is slightly un-uniform, with maximum deviations around 11% and 7% between the maximum and minimum values calculated for OVT and IVT, respectively. However, the predicted minimum velocities for both the OVT (16.8 m/s) and IVT PFU channels (17.7 m/s) result higher than 16 m/s, therefore allowing the pertaining requirement to be fulfilled.

Finally, the distributions of the margin against CHF onset within the VTs PFU cooling channels have been assessed, mainly in order to check whether its prescribed minimum value of 1.5 is guaranteed.

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, whose intensity has been conservatively assumed equal to 20 MW/m^2. Moreover, water coolant has been supposed to flow at the pressure of 5 MPa, at the temperature of 150 °C and with the calculated flow velocity distribution for PFU channels. 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 [5]. Furthermore, assuming a 1.6 peaking factor (f_p), representing the ratio of the maximum heat flux to the coolant to the heat flux arising from plasma and incident onto the PFU armour, the corresponding Incident Critical Heat Flux (ICHF) has been assessed as the ratio of the calculated CHF to f_p. Finally, the margin against the CHF onset has been derived for each VTs PFU channel as the ratio of the calculated distribution of the ICHF to the 20 MW/m^2 nominal heat flux onto the VTs armour plasma-facing surface assumed as reference.

The obtained CHF margin distributions have the analogous behaviour of the velocity distributions previously reported, with minimum and maximum values assessed respectively around 1.6 and 1.7 (fulfilling the prescribed limit of 1.5). In addition, these results attest an acceptably uniform distribution for both the VTs, since maximum deviations between their pertaining maximum and minimum values amount to about 8% and 5%.

3.2. PFCs cooling circuit - Results summary

The results of the steady state CFD analysis of the three lay-out options of the DEMO divertor cassette PFCs cooling circuit have been summarized in table 6.

Table 6. Main results of PFCs cooling circuit CFD analysis.

	Cooling Option 1	**Cooling Option 2**	**Cooling Option 3**
G [kg/s]	60.1	110.2	60.1
Δp [MPa]	1.96	2.95	1.84
Min V_{ax} [m/s] OVT	16.8	14.8	14.7
Min V_{ax} [m/s] IVT	17.7	17.4	17.1
Min CHF margin OVT	1.6	1.4	1.4
Min CHF margin IVT	1.6	1.6	1.6

These results show that, as far as the thermal-hydraulic performances are concerned, the most promising lay-out is Cooling Option 1. On the other hand, it might be argued that Cooling Option 2 is the most interesting lay-out from the standpoint of design simplification. Anyway, even if they substantially fulfil both axial flow velocity and CHF margin requirements, their pressure drops have to be further reduced.

3.3. Revised cooling options CFD analysis

In order to improve the thermal-hydraulic performances of the DEMO divertor cassette PFCs cooling circuit, an optimisation study has been carried out, intended to minimize its total pressure drop under nominal steady state conditions. To this purpose, attention has been specifically focussed on both Cooling Options 1 and 2.

In particular, considering that a significant portion of the calculated pressure drop is predicted along the divertor cassette inlet/outlet manifolds, mainly due to distributed hydraulic resistances that strongly depend on hydraulic diameter, it has been decided to investigate the potential effect on the pressure drop reduction of a manifold diameter increase of a factor 1.3.

The pressure drops across the main sections of these analysed circuits are reported in tables 7 and 8.

Table 7. PFCs revised Cooling Option 1 total pressure drops.

Pressure points	**$\Delta p^{Reference}$ [MPa]**	**$\Delta p^{Revised}$ [MPa]**	**Δ [MPa]**
OVT segment	1.12	0.92	0.20
IVT segment	1.23	0.87	0.36
TOTAL	1.54	1.02	0.52

Table 8. PFCs revised Cooling Option 2 total pressure drops.

Pressure points	**$\Delta p^{Reference}$ [MPa]**	**$\Delta p^{Revised}$ [MPa]**	**Δ [MPa]**
OVT segment	1.63	0.92	0.71
IVT segment	1.84	0.98	0.86
TOTAL	2.52	1.16	1.36

Introducing the swirl tape turbulence promoter, the CFD prediction of total pressure drop has been roughly raised to $\Delta p=1.02+0.39=1.41$ MPa for revised Cooling Option 1 and to $\Delta p=1.16+0.31=1.47$ MPa for revised Cooling Option 2, obtaining in both cases results just slightly higher than the prescribed limit of 1.4 MPa.

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 three different lay-out options of the DEMO divertor PFCs cooling circuit.

Results obtained have indicated very modest coolant thermal rises (lower than 10 °C) for all the investigated PFCs cooling options and calculated margins against the CHF onset substantially above the prescribed threshold of 1.5. Conversely, the estimated total pressure drops have resulted to be higher than the required limit of 1.4 MPa, and the limit on the minimum PFUs axial flow velocity has not always been reached.

As a consequence, revised configurations of Cooling Option 1 and 2 have been also considered, resulting in a significant decrease in the predicted total pressure drop, therefore encouraging a further slight lay-out modification in order to fulfil all the thermal-hydraulic requirements.

Acknowledgments

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