

Hydraulic Assessment of an Upgraded Pipework Arrangement for the DEMO Divertor Plasma Facing Components Cooling Circuit

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Abstract

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 thermal-hydraulic behaviour of the DEMO divertor cassette cooling system, focussing the attention on the latest configuration of the Plasma Facing Components (PFCs) circuit consistent with the DEMO baseline 2017. 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. A CFD analysis has been carried out for the PFCs cooling circuit under nominal steady-state conditions and its thermal-hydraulic performances have been assessed in terms of coolant total pressure drop, flow velocity and Critical Heat Flux (CHF) margin distributions among the Plasma Facing Units (PFUs) channels, to check whether they comply with the corresponding limits. Results have highlighted serious critical issues, such as an intolerable total pressure drop (significantly higher than 1.4 MPa) as well as a insufficient margin against CHF onset (lower than 1.4) within all the PFU channels. Therefore, an optimisation study has been performed to investigate the potential improvements of the PFCs cooling circuit thermal-hydraulic performances due to proper changes of its geometric configuration, focussing the attention on the inlet manifold branch. The study has allowed to select the most effective cooling circuit configuration, that fulfils the maximum pressure drop requirement ($\Delta p < 1.4$ MPa), while raising the minimum CHF margin within the PFU channels. Moreover, it would allow to reduce the ex-vessel total pressure drop, while decreasing the average coolant flow velocity up to values lower than 10 m/s. 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, Thermofluid-dynamics, CFD analysis

1. Introduction

The European research roadmap, drafted to realize commercially viable fusion power generation, has defined reliable power exhausting as one of the most critical missions. Heat-exhaust systems must be capable of withstanding the large heat and particle fluxes of a fusion power plant, allowing, at the same time, as high performance as possible from the core plasma [1].

The divertor is the key in-vessel component in this context. Being responsible for power exhaust and impurity removal via guided plasma exhaust, the viability of

fusion power generation heavily depends indeed on the heat load that can be tolerated by the divertor under normal and off-normal operation [2]. Therefore, particular 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 Work Package DIV 1 - “Divertor Cassette Design and Integration” [3, 4] of the EUROfusion action and in line with previous activities [5, 6, 7, 8, 9], a research campaign has been jointly carried out by University of Palermo (UNIPA) and ENEA to investigate the thermal-hydraulic behaviour of the DEMO divertor Plasma Facing Components (PFCs) cooling system .

Attention has been initially focussed on the layout of the PFCs cooling circuit released in early 2019 and

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consistent to DEMO Baseline 2017 [10], assessing its steady-state thermal-hydraulic performances. These latter shall comply with the requirements on pressure drop ($\Delta p < 1.4$ MPa), CHF margin (>1.4) and flow distribution among PFU channels.

Then, according to the issues arisen from this first thermal-hydraulic assessment, the PFCs cooling circuit layout has been optimised focussing the attention on the inlet manifold branch, thus allowing for a significant pressure drop reduction.

As a consequence, a second optimised PFCs cooling circuit layout has been released in 2019, taking into account both the indications given by thermal-hydraulic calculations and some manufacturing considerations [11]. The thermal-hydraulic performances of this upgraded PFCs cooling circuit have been numerically assessed under nominal steady-state conditions to check whether the aforementioned requirements are met.

The research campaign has been performed following a computational approach based on the finite volume method and adopting the ANSYS CFX v.19.2 Computational Fluid-Dynamic (CFD) code [12], already used in similar studies [13] and adopted to evaluate concentrated hydraulic resistances to be used in system codes [14, 15]. Models and assumptions are herein reported and discussed, together with the main results obtained.

2. Outline of 2019 DEMO divertor cassette and PFCs

According to its 2019 design [16], DEMO divertor is articulated in 48 toroidal cassettes, each composed of a Cassette Body (CB), equipped with a Liner and two Reflector Plates (RPs), and supporting two PFCs (fig. 1). These latter are named Inner and Outer Vertical Target (IVT, OVT), and are composed of actively cooled Plasma Facing Units (PFUs) equipped with a Swirl Tape (ST) turbulence promoter.

The PFCs cooling circuit (fig. 2) has been developed by the cooperation between UNIPA thermal-hydraulic research unit and the Divertor CAD team; it is characterised by two main segments, devoted to separately feed coolant to the 31 PFU channels of the IVT and the 43 channels of the OVT, connected in parallel by three-way connections to the inlet and outlet feeding pipes.

3. PFCs cooling circuit CFD analysis

The thermal-hydraulic performances of the PFCs cooling circuit under the coolant operative conditions of

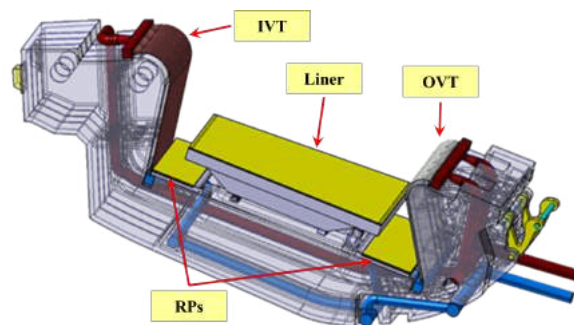


Figure 1: DEMO Divertor cassette (Design 2019).

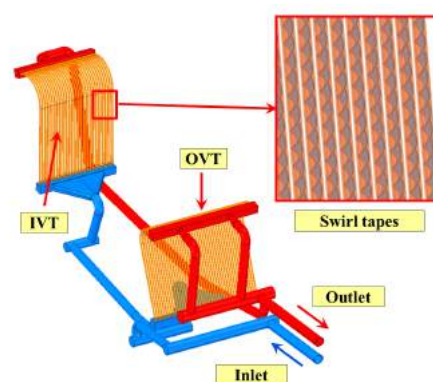


Figure 2: DEMO Divertor PFCs (Design 2019).

table 1 [16] have been assessed by running steady-state, isothermal CFD analyses, where the temperature of the fluid inside the PFCs has been supposed to be equal to the average value between inlet and outlet sections, evaluated by means of simple thermodynamic calculations. Moreover, realistic configurations with swirl tape turbulence promoters inside each PFU cooling channel have been considered.

Table 1: Summary of PFCs coolant reference operative conditions.

	Reference Conditions
Inlet Pressure [MPa]	5.0
Inlet Temperature [°C]	130
Removed Power [MW]	136
G per Cassette [kg/s]	98.63

The mesh parameters selected for the PFCs cooling circuit are reported in table 2, while some details of the mesh set up for the CFD analysis are shown in fig. 3. Furthermore, the adopted main assumptions, models and Boundary Conditions (BC) are reported in table 3. It is worth highlighting that the adopted meshing strategy and numerical modelling have been chosen on the

basis of previous validation and mesh sensitivity analyses, and it has been selected in order to guarantee a good compromise between solution accuracy and computational costs.

Table 2: Summary of the main mesh parameters.

Mesh Parameter	Value
Nodes	$4.0 \cdot 10^7$
Elements	$5.5 \cdot 10^7$
Elements Topology	Hybrid (Tetras/Wedges)
Inflation Layers Number	12
First Layer Thickness [μm]	12
Layers Growth Rate	1.4
Typical Element Size [m]	$2.39 \cdot 10^{-3}$
Surface with $y^+ < 100$ [%]	100

Table 3: Summary of PFCs CFD analysis setup.

	Reference Conditions
Analysis Type	Steady-state Isothermal
Material Library	Water IAPWS IF97 [17]
Temperature [$^{\circ}\text{C}$]	133
Turbulence Model	k- ϵ
Boundary Layer Modelling	Scalable Wall Functions
Absolute Wall Roughness [μm]	2
Inlet Pressure [MPa]	5
Outlet Mass Flow Rate [kg/s]	98.63

The coolant total pressure spatial distribution within the PFCs cooling circuit is reported in fig. 4, while total pressure drops across the main sections of the circuit (fig. 5) are reported in table 4, where the presence of the ST turbulence promoters is clearly shown by IVT and OVT high pressure drops.

Table 4: PFCs cooling circuit total pressure drop distribution.

Sections	Pressure points	Δp [MPa]
Inlet Manifold	IM_A - IM_B	0.4455
IVT Inlet 3Way	IM_B - IVT_A	0.7543
Inlet IVT Manifold	IVT_A - IVT_B	0.0688
IVT	IVT_B - IVT_C	0.7429
Outlet IVT Manifold	IVT_C - IVT_D	0.0581
IVT Outlet 3Way	IVT_D - OM_A	0.1781
OVT Inlet 3Way	IM_B - OVT_A	0.6887
OVT	OVT_A - OVT_B	0.9180
OVT Outlet 3Way	OVT_B - OM_B	0.2658
TOTAL	IM_A - OM_B	2.3179

As it may be argued from the obtained results, the PFCs cooling circuit overall total pressure drop amounts to ≈ 2.3 MPa, resulting significantly higher than the prescribed limit of 1.4 MPa. It is worth highlighting that most of the overall total pressure drop (≈ 0.9 MPa) is

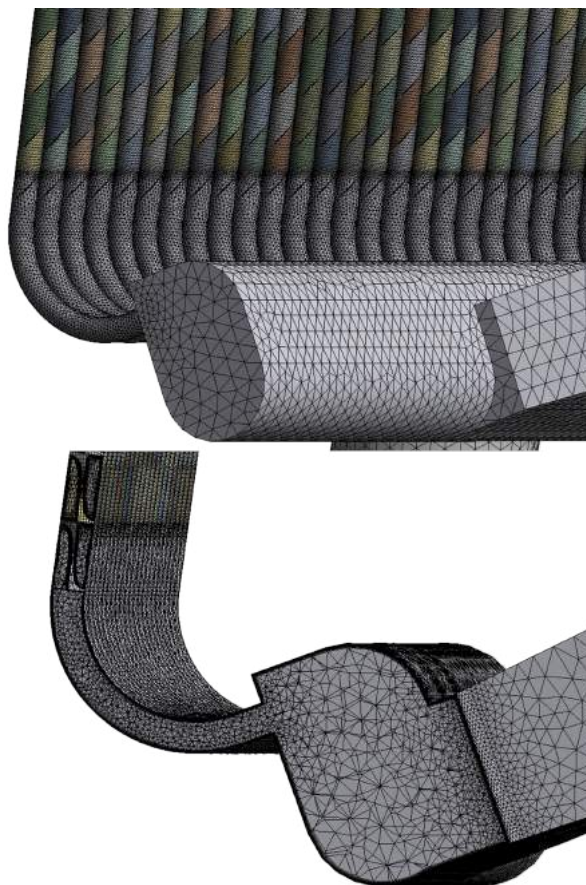


Figure 3: Mesh adopted for PFCs cooling circuit CFD analysis.

located at the 3-way connections between inlet/outlet manifolds and OVT/IVT branching with particular reference to the inlet connection (≈ 0.7 MPa), as reported in table 4, posing then the need for a deep revision of the cooling circuit pipework.

Additionally, in order to check whether unbalanced distributions might take place within the circuit preventing a uniform cooling of its solid components, the distributions of the coolant axial flow velocity among the PFU channels of both the VTs have been assessed and they have been reported in fig. 6, summarising their key-parameters in table 5.

Table 5: Coolant axial flow velocity distribution key-parameters.

	OVT	IVT
Max V_{ax} [m/s]	15.78	12.98
Min V_{ax} [m/s]	14.51	12.06
$\epsilon_{Max-Min}$ [%]	8.03	7.14
Average V_{ax} [m/s]	14.83	12.47
Std. Deviation [m/s]	0.31	0.22

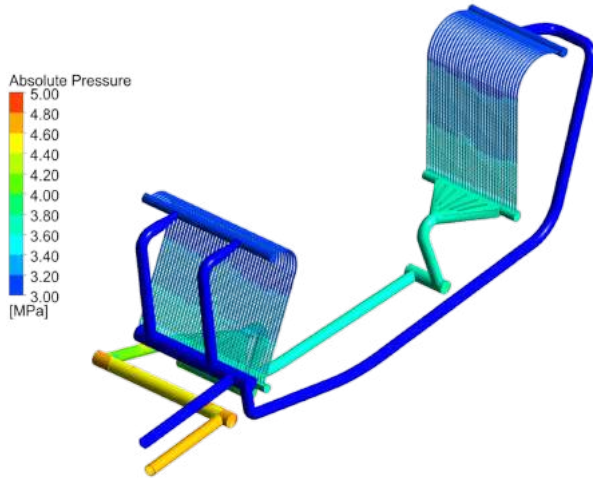


Figure 4: PFCs coolant total pressure field.

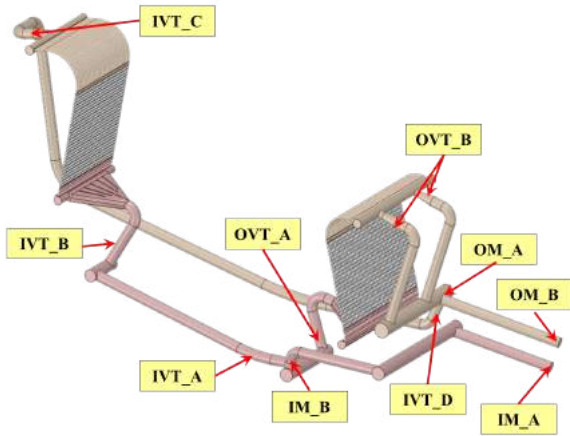


Figure 5: PFCs cooling circuit main sections.

From the analysis of the results obtained, it may be argued that the distribution of coolant axial flow velocity is acceptably uniform for each PFU channel, for both the VTs, since maximum deviations in the order of 8% and 7% have been estimated between the maximum ($\text{Max } V_{ax}$) and minimum ($\text{Min } V_{ax}$) values calculated as for OVT and IVT, respectively. As a further confirmation, the standard deviations calculated for both the two axial flow velocity distributions amount to ≈ 0.3 and ≈ 0.2 m/s, respectively, resulting to be quite low.

The distributions of the margin against CHF onset within VTs PFU channels have been assessed in order to check whether its prescribed minimum value of 1.4 is guaranteed by the circuit layout. Attention has been paid to the strike point sections of VTs, where the peak heat flux from plasma (20 MW/m^2 [16]) has been sup-

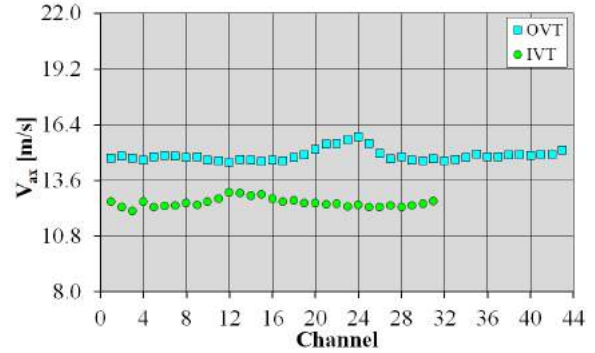


Figure 6: Coolant axial flow velocity distribution among OVT and IVT PFU channels.

posed to be located. With the procedure reported in [7], based on the correlation of [18], the CHF at the interface between coolant and channel walls has been calculated for each PFU channel. The distributions obtained have been reported in fig. 7 along with their key-parameters in table 6. From the analysis of the results obtained, it

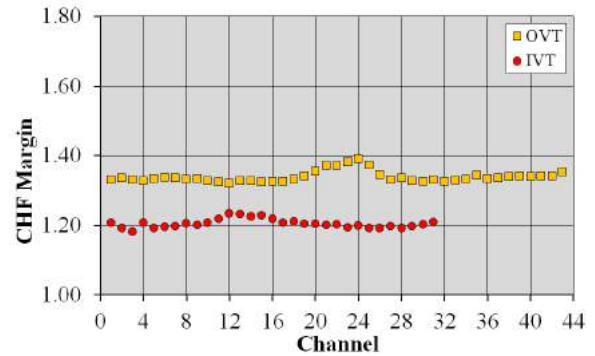


Figure 7: CHF margin distribution among OVT and IVT PFU channels.

Table 6: Coolant axial flow velocity distribution key-parameters.

	OVT	IVT
Max CHF Margin	1.34	1.35
Min CHF Margin	1.24	1.27
$\epsilon_{\text{Max-Min}}[\%]$	7.16	5.60
Average CHF Margin	1.27	1.29
Std. Deviation	0.03	0.01

may be argued that, despite the calculated distributions of CHF margin are acceptably uniform for both the VTs, the CHF margin values calculated for both VTs PFU channels result always lower than the prescribed limit of 1.4.

4. Design optimization

The performed analyses have highlighted the need for a revision of the PFCs layout, mainly intended to reduce both distributed and concentrated hydraulic resistances at the inlet/outlet manifold branches. Therefore, focussing the attention on the inlet manifold branch of the analysed PFCs cooling circuit, the thermal-hydraulic performances of selected revised configurations have been assessed by running local, steady-state, isothermal CFD analyses.

At first, since both distributed and concentrated hydraulic resistances strongly depends on the manifold hydraulic diameter, it has been decided to investigate the potential effect of the manifolds diameter increase on the total pressure drop reduction. Therefore, it has been considered a revised inlet manifold branch layout, namely V0.1, characterized by inlet common manifold diameter increased from 70 mm to 98 mm and single PFC manifold diameter increased from 70 mm to 75 mm. A comparison between the original inlet manifold branch configuration and the configuration V0.1 is shown in fig. 8. Results show that the total pressure

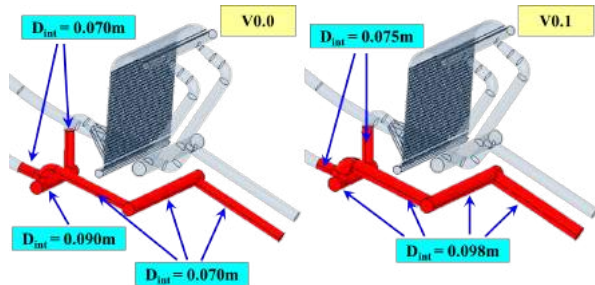


Figure 8: PFCs inlet branching V0.0 and V0.1 layout comparison.

drop calculated for the original inlet manifold branch configuration amounts to 1.248 MPa, in agreement with the results obtained for the complete PFCs cooling circuit. Conversely, the total pressure drop predicted for the configuration V0.1 amounts to 0.935 MPa with a margin from the original layout of 0.313 MPa ($\approx 25\%$).

As a second step, in order to further reduce the contribution of the inlet manifold branch to the overall total pressure drop, it has been conceived a revised inlet manifold branch layout, namely V1.1, where sharp elbows have been replaced by smooth curves and the branch layout has been modified so to ease coolant flowing towards the PFCs while keeping unaltered the pipe scheme and the manifold diameters. Configuration V1.1 is shown in fig. 9 along with the original one. Results show that the total pressure drop calculated for the configuration V1.1 amounts to 0.307 MPa with a margin

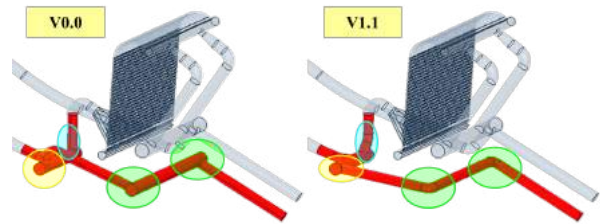


Figure 9: PFCs inlet branching V0.0 and V1.1 layout comparison.

from the original layout of 0.941 MPa ($\approx 75\%$). The considered solution might fulfil the maximum pressure drop requirement ($\Delta p < 1.4$ Mpa). Nevertheless, total pressure drop along the PFCs cooling circuit shall be further reduced, whenever possible, in order to increase as much as possible the average total pressure and thus the minimum CHF margin within the PFU channels. Moreover, layout simplification might help manufacturing and remote maintenance procedures.

Therefore, a third revised inlet manifold branch layout, namely V2.0, has been conceived. A comparison between the configuration V1.1 and configuration V2.0 is shown in fig. 10. Results show that configuration

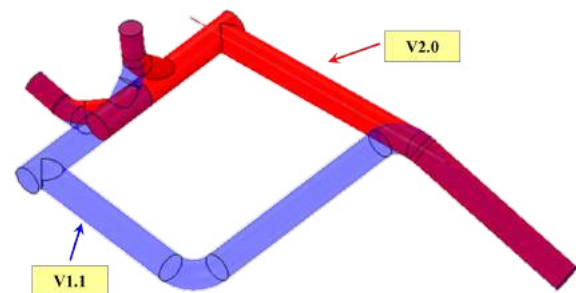


Figure 10: PFCs inlet branching V1.1 and V2.0 layout comparison.

V2.0 has allowed a further pressure drop reduction of 0.113 MPa with an overall margin from the original layout of 1.055 MPa ($\approx 85\%$).

At a later stage, a further design change has been deemed necessary following some considerations of the Work Package Balance of Plant (WPBoP). In fact, considering the present PFCs cooling circuit layout (V0.0), an average coolant flow velocity of ≈ 28 m/s may be calculated for the feeding manifolds that brings to an average pressure drop per unit length of ≈ 0.1 MPa/m and, consequently, to an unacceptably high pumping power. Therefore, it has been issued a revised inlet manifold branch layout, namely V2.1, that is charac-

terized by DN125 and DN90 (sch. 10) pipes for the common manifolds and for the OVT/IVT manifolds, respectively, aiming at reducing the ex-vessel total pressure drop while decreasing the average coolant flow velocity up to values lower than 12 m/s [19]. A visual comparison of configurations V2.0 and V2.1 is shown in fig. 11. Results show that configuration V2.1 has al-

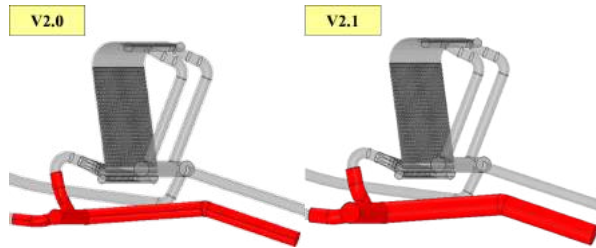


Figure 11: PFCs inlet branching V2.0 and V2.1 layout comparison.

lowed a further pressure drop reduction of 0.139 MPa with an overall margin from the original layout of 1.194 MPa ($\approx 96\%$). As an additional improvement, configuration V2.1 has allowed to reduce the ex-vessel total pressure drop per unit length up to ≈ 0.004 MPa/m, which is totally in line with the needs of the WPBoP, while decreasing the average coolant flow velocity up to a value of ≈ 8 m/s.

The results of the selected inlet manifold branch optimization loop are summarized in table 7 and in fig. 12.

Table 7: PFCs cooling circuit inlet branching optimization summary.

Version	Δp [MPa]	$\Delta(\Delta p)$ [MPa]
V0.0	1.2481	-
V0.1	0.5465	0.7016
V1.1	0.3068	0.9413
V2.0	0.1934	1.0547
V2.1	0.0545	1.1936

5. Upgraded PFCs cooling circuit CFD analysis

On the basis of the optimization results and of some manufacturing considerations, the Divertor CAD team revised the PFCs cooling circuit layout, introducing similar improvements also for the outlet manifold branching schemes. The mesh parameters selected for the considered PFCs cooling circuit are similar to those reported in table 2, while the adopted main assumptions, models and boundary conditions are the same of table 3.

The coolant total pressure spatial distribution for the upgraded configuration is reported in fig. 13, while total pressure drops across the main sections of the circuit

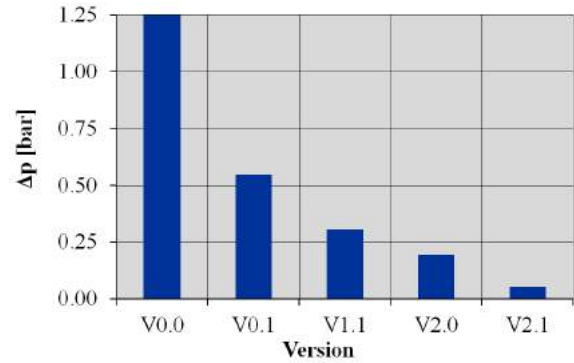


Figure 12: PFCs cooling circuit inlet branching optimization summary.



Figure 13: PFCs coolant total pressure field.

(fig. 5) are reported in table 8. As it may be argued from the obtained results, the upgraded PFCs cooling circuit overall total pressure drop amounts to ≈ 0.94 MPa, resulting considerably lower than the prescribed limit of 1.4 MPa. In particular, the optimised PFCs cooling circuit shows its effectiveness at the OVT/IVT branches, where the total pressure drop was reduced by more than 90% with respect to the baseline PFCs design.

In addition, the distributions of the coolant axial flow velocity among the PFU channels of both the VTs have been reported in fig. 14 along with their key-parameters in table 9.

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 acceptably uniform, with values in line with the baseline configuration.

Concerning the distributions of the margin against CHF onset within the VTs PFU cooling channels, they

Table 8: PFCs cooling circuit total pressure drop distribution.

Sections	Pressure points	Δp [MPa]
Inlet Common Manifold	IM_A - IM_B	0.0038
IVT Inlet 3Way	IM_B - IVT_A	0.0541
Inlet IVT Manifold	IVT_A - IVT_B	0.0311
IVT	IVT_B - IVT_C	0.7958
Outlet IVT Manifold	IVT_C - IVT_D	0.0229
IVT Outlet 3Way	IVT_D - OM_A	0.0358
OVT Inlet 3Way	IM_B - OVT_A	0.0581
OVT	OVT_A - OVT_B	0.8815
OVT Outlet 3Way	OVT_B - OM_B	0.0002
TOTAL	IM_A - OM_B	0.9436

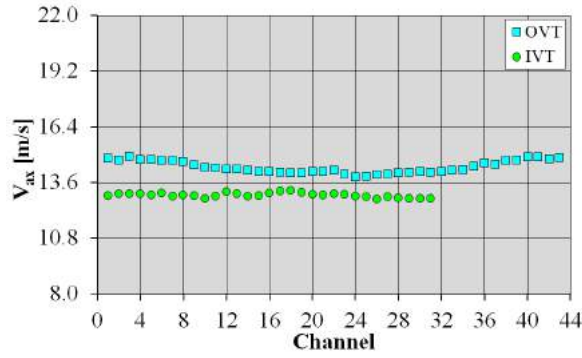


Figure 14: Coolant axial flow velocity distribution among OVT and IVT PFU channels.

have been reported in fig. 15 along with their key-parameters in table 10.

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, the values of CHF margin calculated for both VTs PFU channels result higher than the prescribed limit of 1.4 in every single PFU channels, being its lowest value equal to 1.41. It is worth mentioning how the CHF margin improvement with respect to the baseline PFCs cooling circuit design can be related to the reduced pressure losses inside the circuit.

Table 9: Coolant axial flow velocity distribution key-parameters.

	OVT	IVT
Max V_{ax} [m/s]	14.91	13.18
Min V_{ax} [m/s]	13.85	12.76
$\epsilon_{Max-Min}$ [%]	7.11	3.18
Average V_{ax} [m/s]	14.37	12.95
Std. Deviation [m/s]	0.32	0.12

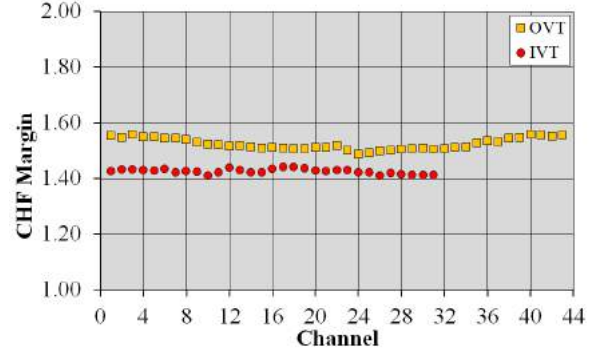


Figure 15: CHF margin distribution among OVT and IVT PFU channels.

Table 10: Coolant axial flow velocity distribution key-parameters.

	OVT	IVT
Max CHF Margin	1.56	1.44
Min CHF Margin	1.49	1.41
$\epsilon_{Max-Min}$ [%]	4.51	2.15
Average CHF Margin	1.52	1.43
Std. Deviation	0.02	0.01

As a matter of fact, an increment of the average pressure inside the circuit increases the CHF value, thus improving the CHF margin.

6. Conclusions

Within the framework of the activities promoted by the EUROfusion consortium, a research campaign has been carried out by University of Palermo and ENEA to study the thermal-hydraulic behaviour of DEMO diverter cassette cooling system, focussing the attention on the PFCs cooling circuit 2019 configuration.

A theoretical-computational approach based on the finite volume method has been followed and the ANSYS CFX code has been adopted.

The PFCs cooling circuit nominal thermal-hydraulic performances have been assessed in terms of coolant total pressure drop, flow velocity and CHF margin distributions. Obtained results have indicated a pressure drop significantly higher than the prescribed limit and amounting to ≈ 2.32 MPa, mainly due to the hydraulic resistances of the 3-way connections between inlet/outlet manifolds and OVT/IVT branching. Therefore, in order to evaluate the potential thermal-hydraulic performance improvement related to a design revision of these components, a localized optimization study has been performed, showing a good margin to reduce the overall pressure drop.

On the basis of the optimization results, a revised PFCs cooling circuit layout has been devised that allowed to obtain a significantly lower pressure drop, amounting to ≈ 0.94 MPa, and an improvement of both flow uniformity and CHF margin inside the PFU channels.

CRedit authorship contribution statement

P.A. Di Maio: Conceptualization, Methodology, Investigation, Writing - original draft. **R. Burlon:** Conceptualization, Methodology, Investigation, Writing - original draft. **G. Mazzone:** Conceptualization, Methodology, Investigation, Writing - original draft. **A. Quartararo:** Conceptualization, Methodology, Investigation, Writing - original draft. **E. Vallone:** Conceptualization, Methodology, Investigation, Writing - original draft. **J.H. You:** Conceptualization, Methodology, Investigation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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