Fusion Engineering and Design 203 (2024) 114467

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Selection of EU-DEMO divertor operating conditions: water cooling thermal-hydraulic parameters and power exhaust capabilities

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ARTICLE INFO

Keywords:
DEMO
Divertor
Water-cooling
Thermo-hydraulic

ABSTRACT

In the context of EUROfusion activities for the development of the DEMO reactor project, the divertor design is a major challenge. It must sustain very high heat, ion particle and neutron fluxes allowing, at the same time, the shielding of the vacuum vessel and the vacuum pumping for reducing the plasma pollution. The conceptual divertor design is based on the use of EUROFER97 for the divertor cassette body, while tungsten monoblocks bonded to CuCrZr pipes are used for plasma-facing targets. EUROFER97 was selected considering its reduced long-term activation and superior creep and swelling resistance under neutron irradiation. However, depending on the operating temperature under neutron irradiation, a pronounced shift of the Ductile to Brittle Transition Temperature (DBTT) is expected. At the same time, for the plasma-facing targets, the coolant temperature has to be identified such to allow sufficient heat removal capacity at the strike point. This study explores alternative cooling conditions for the divertor system that are able to ensure the fulfillment of functional and system requirements and to allow for divertor cassette body re-use during plant lifetime. The main aim is to identify the best water cooling thermal-hydraulic conditions avoiding material embrittlement (for EUROFER 97) and softening/hardening (for copper alloy pipes). At the same time, the goal is to reduce the inventories (enthalpy of the cooling circuit) and the radwaste at the end of divertor lifetime.

1. Introduction

In the development of a power plant fusion reactor the divertor system plays a pivotal role, as the divertor configuration is one of the main challenges to be addressed. The divertor system has to sustain very high heat fluxes due to the ion particle exhaust while it is subjected to intense neutron fluxes allowing, at the same time, the shielding of the vacuum vessel as well as the vacuum pumping to reduce the plasma pollution. In the context of the EUROfusion research activities, the Pre-Conceptual Design (PCD) Phase was concluded in late 2020. On this occasion, the divertor baseline design and the key technology options were identified [1]. Following the Gate 1 review, the divertor design configuration is being slightly revised in the current Conceptual Design Phase, with the main aim to re-use main components and replace, during maintenance operation in an Active Maintenance Facility, plasma-facing targets. The main goal is the reduction of the inventories (enthalpy of the cooling circuit) and of the radwaste at the end of the divertor life. Such current divertor configuration is composed of the following main parts (Fig. 1): i) Cassette Body (CB), ii) Shielding Liner (SL), iii) Reflector Plates (RPs), iv) Vertical Targets (VTs). The VTs are then composed of a main body (named VTs bodies) supporting Plasma Facing Units (PFUs) (Fig. 2).

According to baseline design, EUROFER97 is used as structural material for the CB, SL and RPs (the SL and RPs have also an armour of plasma-spayed Tungsten (W)), while the VTs bodies can be either EUROFER97 or AISI 316 L. PFUs are made of Tungsten monoblocks (plasma facing) bonded to CuCrZr pipes.

EUROFER97 was selected considering its reduced long-term activation and superior creep and swelling resistance under neutron irradiation [2]. However, depending on the operating temperature under neutron irradiation, a pronounced shift of the Ductile to Brittle Transition Temperature (DBTT) is expected. At the same time, for the VTs, the

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https://doi.org/10.1016/j.fusengdes.2024.114467
Received 13 October 2023; Received in revised form 12 April 2024; Accepted 19 April 2024
Available online 23 April 2024

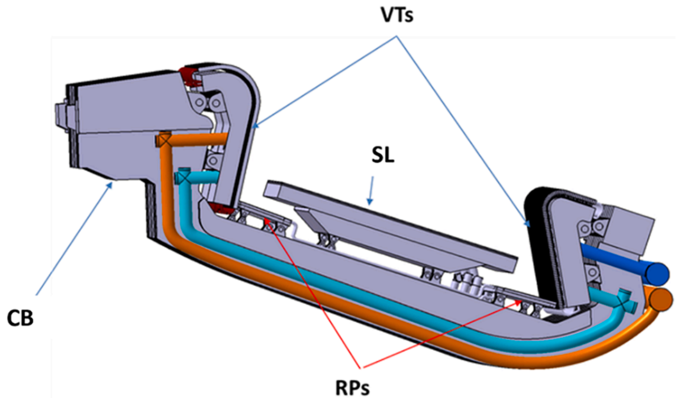

Fig. 1. Divertor configuration at Conceptual Design Phase.

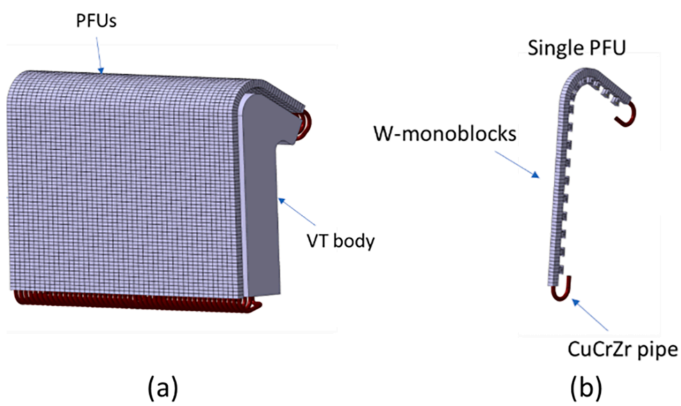

Fig. 2. (a) Vertical Targets composition, (b) Single PFU composition.

coolant temperature level has to be defined such to allow sufficient heat removal capacity at the strike point. Given these "competing" requirements, the divertor is equipped with two different cooling circuits, one for the EUROFER97 components and the other for the VTs. Details on pre-conceptual coolant temperature selection and design of the cooling loops are available in [2–5].

The main aim of this work is to re-assess the coolant temperatures and identify suitable operating conditions for the divertor system that are able to ensure the fulfilment of functional and system requirements and to allow for divertor cassette body re-use during plant lifetime. In other words, we identified the best water coolant thermal-hydraulic conditions to avoid EUROFER97 material embrittlement (in Section 2), and CuCrZr softening/hardening (in Section 3).

2. Temperature levels for divertor cassette body, shielding liner and reflector plates

2.1. Requirements for EUROFER97 components

EUROFER97 is selected as divertor CB structural material for its reduced long-term activation and low tendency to swelling behavior under neutron irradiation. On such basis, the general criterium adopted for minimum coolant temperature selection is related to the material behavior under neutron irradiation, aiming to keep the structural material in a range of temperatures allowing sufficient ductile behavior during the operation but also during maintenance. In PCD stage, considerations about the effects of temperature, irradiation and helium production on DBTT and Fracture Toughness Transition Temperature (FTTT) were investigated, selecting the minimum coolant temperature at 180 °C assuming a divertor lifetime of 1.5 full power year (fpy), as discussed in [2].

However, extrapolating the design choice to reactor level, the 1.5 fpy lifetime poses a serious question of waste management, especially in terms of volume and mass of waste. Options assuming a longer operating period and the re-use of CB after, eventually, annealing shall be investigated. Additionally, data on FTTT and DBTT are not extensive and "consolidated", since relevant tests are carried out at irradiation temperatures of 300–330 °C [6]. Considering also the uncertainties on the Helium production effects on DBTT, a safety margin shall be considered.

The revision of the operating coolant temperature for EUROFER97 components discussed in this paper is based on the following *driving requirements*: i) Divertor lifetime is set at *2 fpy*; ii) To keep the structural material in a range of temperatures allowing sufficient ductile behavior, considering also the possibility to re-use the CB after recovering. In such evaluation, *DBTT is assumed as reference parameter* for the operating temperature selection, assuming the possibility to verify the components behavior by means of fracture mechanic assessment in the transition region. Additionally, a safety margin is considered to ensure that structural material never undergoes the risk of operating in brittle conditions (e.g. in case of malfunction in the Balance of Plant, as feedwater regulating valve failure).

2.2. Identification of temperature level for EUROFER97 components

Figs. 3 and 4 show, respectively, maps of dpa/fpy and Helium production [appm/fpy] in divertor EUROFER97 components [7]. Peak values are located on the top layers of the SL, where maximum values of ≈5 dpa/fpy and ≈100 appm/fpy are calculated.

Considering 2 fpy, the shift in DBTT due to neutron damage and He production is evaluated basing on the data reported in [6].

As shown in Fig. 5, with a damage level at 10 dpa/2fpy a shift in DBTT of ≈170 °C is expected. Regarding the He production (Fig. 6), a DBTT shift in the range of 0.5–0.6 K/appm is estimated based on Charpy impact experiments on boron doped model steels [6]. Hence for our case of 200 appm/2fpy an additional shift of the DBTT of ≈120/140 °C is expected.

According to [2] and [6], the average DBTT in the un-irradiated condition is about −80 °C: according to the shift at 2 fpy discussed above, the DBTT shifts from −80 °C to ≈210/230 °C (1).

$$T_{DBTT\ at\ 2FPY} = -80\ ^{\circ}C + 170^{\circ}C + [120-140]^{\circ}C \approx [210-230]\ ^{\circ}C \quad (1)$$

With the margins needed for the minimum inlet temperature of the primary coolant to ensure that structural material never undergoes the risk of operating in brittle conditions, *the PWR conditions are selected for Divertor EUROFER97 components*, assuming an inlet temperature in the range 285–295 °C and inlet pressure of 15.5 MPa and an outlet temperature range of 320–328 °C.

As an additional advantage, the PWR conditions are used also for EUROFER97 components in DEMO (Breeding Blanket (BB)), so this choice for the divertor could simplify plant integration.

On the other side, high pressure requires thicker pipes that impacts (re-) welding conditions, and requires a new feasibility analysis of Remote Handling (RH) operation. The risk analyses shall be also updated.

3. Vertical targets temperature levels

3.1. Constraints, parameter and requirements for the selection of VTs operating conditions

Concerning the VTs, the investigation of suitable cooling water conditions has been carried out by performing parametric thermal-hydraulic analyses, adopting the numerical tool ADRANOS, described in [8] and validated against the experimental results reported in [9]. This tool is designed to evaluate the performance map of the cooling circuit by adopting both a lumped-parameter approach to calculate the temperature and pressure distribution inside the circuit and a

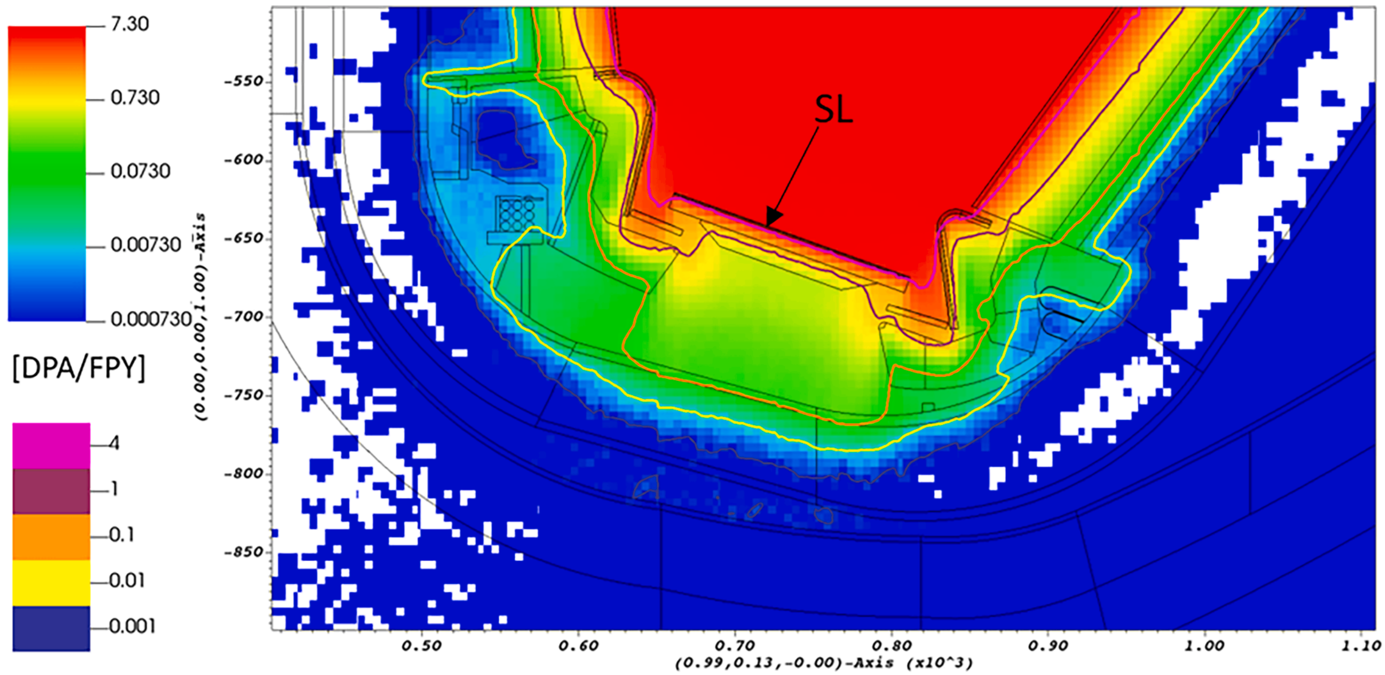

Fig. 3. . dpa/fpy in EUROFER97 [7].

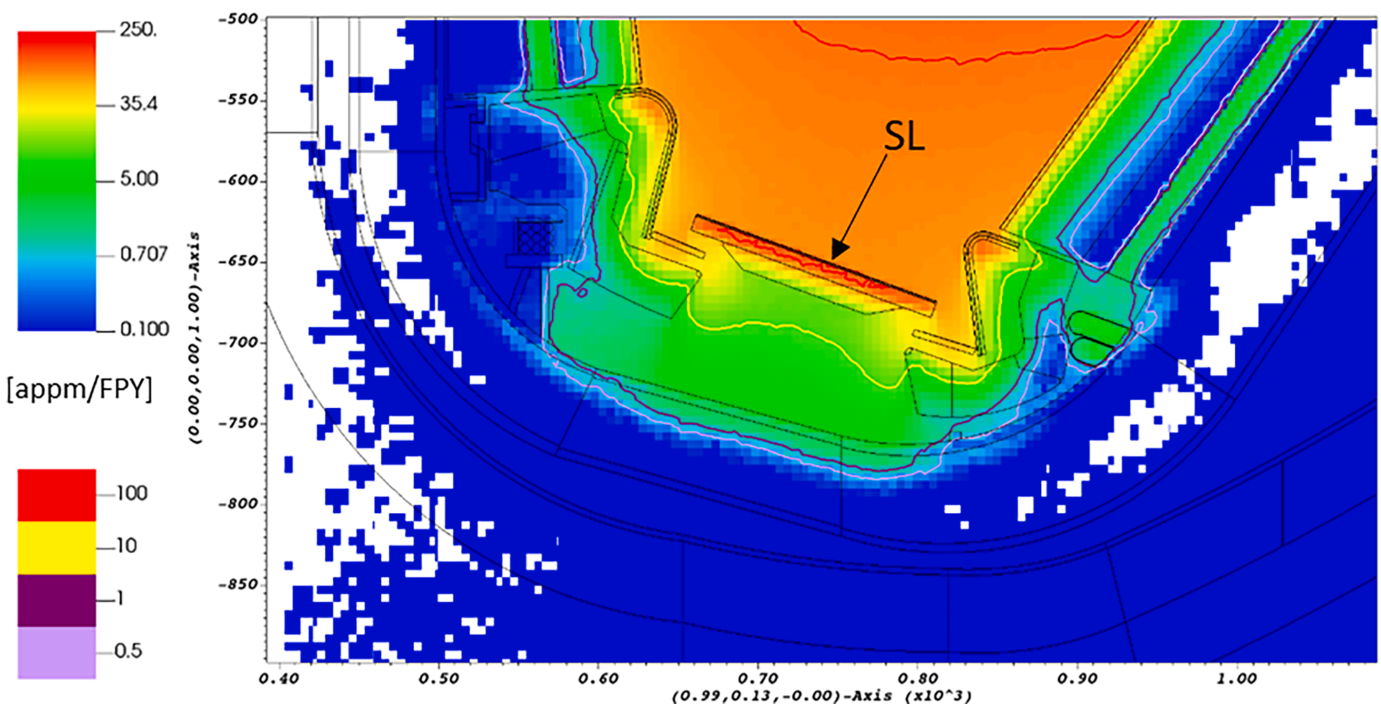

Fig. 4. He production in EUROFER97 [7].

finite-element thermal module to evaluate the steady-state temperature distribution inside the monoblocks through 2D analyses. The parametric analyses are performed considering a steady-state peaked plasma heat flux of 10 MW/m^2, representative of normal operating conditions during flat-top, while three different slow-transient heat load scenarios were evaluated, namely 20, 25 and 30 MW/m^2 (assuming the same peaked profile as 10 MW/m^2), to assess how the maximum plasma heat fluxes expected during plasma operation may influence the operating map. These slow-transient heat loads are supposed to be sufficiently long (some 10 s of seconds) such as to establish thermal equilibrium in the VTs, and thus the temperature distribution can be evaluated by adopting steady-state thermal analyses. Additionally, the analyses considered the realistic pressure drops in both of the VTs cooling circuits and of the DIV-VT primary heat transfer system (PHTS), the temperature distribution inside the monoblocks, and the potential occurrence of Critical Heat Flux (CHF). An additional limit on maximum coolant velocity is moreover considered to assess potential fretting issues due to the twisted tape in the straight VT pipe and flow-induced corrosion. The ranges obtained are not sufficient to assess the complete performance of the component and must be successively verified in terms of structural

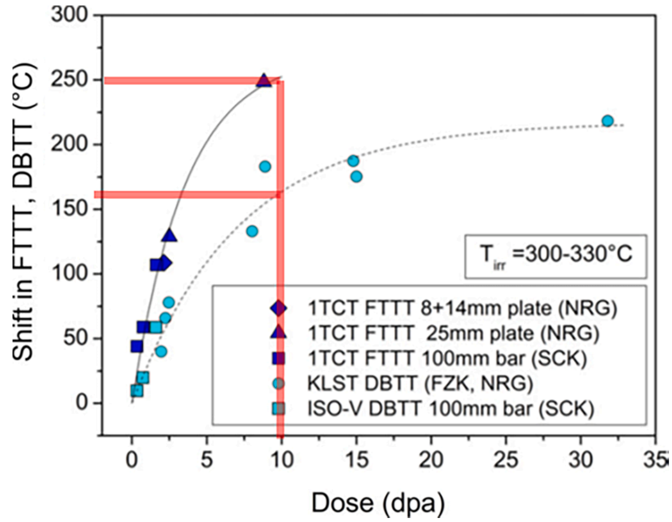

Fig. 5. Irradiation-induced shift in FTTT and DBTT for EUROFER97 [6].

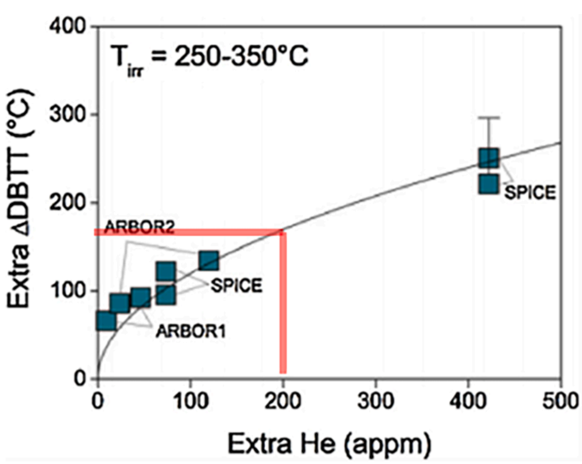

Fig. 6. Helium-induced extra embrittlement vs extra helium amount for irradiated boron doped steels [6].

response and expected lifetime due to neutron-induced damage of the PFUs and their supporting structures.

The parametric analyses were carried out considering two alternative design configurations for the cooling circuit of the two VTs, namely the Inner Vertical Target (IVT) and the Outer Vertical Target (OVT), connected in series, in the first reference case (as the current baseline design shown in Fig. 1) and in parallel in the second configuration. The analyses were performed by considering the following list of selected constraints which may endanger the function of the divertor in operation from the thermal-hydraulic perspective. These constraints are relevant to the monoblock temperatures (namely for Cu, CuCrZr and Tungsten), the cooling circuit performances and the maximum fluid velocities inside the PFU cooling tubes.

A. CHF safety margins higher than 1.4 were checked both for the IVT and the OVT, considering the heat flux selected for the specific scenario. Additionally, a scenario with CHF safety margins higher than 1.2 was included, to reduce the conservativeness of this constraint, to explore the range of reachable higher heat fluxes in these conditions. The CHF margins are conservatively calculated considering the fluid temperature and static pressure at the outlet of the twisted tape section of the VTs, so to account for possible displacements of the strike point (e.g. due to sweeping).
B. A maximum allowable total pressure drop curve, to be considered as the maximum net value that can be spent inside the VT cooling circuit, was obtained supposing a pump head for the DIV-VT PHTS of 230 m and taking into account the pressure drop inside the PHTS itself. It should be noted that, at low mass flow rates, a reduction of the size of the various pipes and equipment of the PHTS was performed, maintaining a minimum PHTS pressure drop of ≈5 bar while ensuring a reduction in water inventory.
C. A maximum coolant axial velocity inside the PFU cooling tubes of 16, 12 and 10 m/s was considered, intended as the maximum value among the different cooling tubes constituting a single PFU assembly. These three values were selected to provide potential limits, in the case fretting issues and flow-induced corrosion are proven to pose a risk to the component integrity and are calculated both for the IVT and OVT.
D. A minimum margin against coolant saturation of 20 °C inside the cooling circuit was considered.
E. Maximum CuCrZr temperatures lower than 300 °C during normal operating conditions [11] i.e. when the component is exposed at most to heat fluxes in the order of 10 MW/m^2, were considered both for IVT and OVT.
F. Maximum CuCrZr temperatures lower than 450 °C [11] during slow-transient overpower events considering high heat fluxes (≥20 MW/m^2), were calculated both for OVT and IVT.
G. Maximum Tungsten temperature lower than the melting temperature of 3442 °C, were considered both for OVT and IVT.
H. Maximum Copper interlayer temperatures lower than 855 °C [11] to guarantee an acceptable design margin against copper melting, were calculated both for IVT and OVT.

A summary of the constraints considered, along with the colour legend adopted in the following, is reported in Table 1. A few constraints are responsible for the definition of the suitable operative conditions, namely the pressure drop, the maximum PFU cooling tube axial velocity, the CHF margin and the Tungsten melting. Other constraints can limit the operating map of the VTs cooling circuit when considering different ranges of operating conditions or different monoblock geometries.

3.2. *Identification of temperature level for VTs*

The operating map of the VTs water cooling circuit was calculated by considering the inlet coolant temperature ranging between 70 and 180 °C, the coolant mass flow rate between 10 and 60 kg/s, and the coolant inlet pressure between 50 and 75 bar. For each triplet of coolant inlet pressure, inlet temperature and mass flow rate the code evaluates the pressure distribution across each of the main sections of the cooling circuit (inlet and outlet manifolds, OVT and IVT) and estimates a distribution of mass flow rates between components connected in parallel (if any), based on the hydraulic characteristic curves drawn from the 3D-CFD simulations. Similarly, the temperature distribution among the different components is obtained and employed to calculate the CHF margin. Finally, 2D thermal analyses are performed to assess the temperature field inside the monoblocks and to check the compliance with the relevant temperature limits.

The results obtained for the reference configuration (Fig. 1, *VTs connected in series*) are depicted from Figs. 7 to 9, respectively for the 10, 20 and 30 MW/m2. The results are presented for two different values of inlet pressure (50 bar and 75 bar, respectively left and right columns) and for the three maximum axial coolant velocities inside the PFU tubes of 16, 12 and 10 m/s (top, middle and bottom rows, respectively). For the sake of synthesis, the full set of results is reported only for the 10 and 20 MW/m^2, while for 30 MW/m^2 only the maps obtained at higher coolant velocity (16 m/s) are shown in this paper. The full set of results (including calculations for 25 MW/m2) is reported in [10].

In Figs. 7 and 8 the green region defines the cooling circuit operation

Table 1
Constraints considered for the parametric analyses.

Color	ID	Constraint	Region	Load [MW/m^2]
	A	M_{CHF}= 1.4, 1.2, 1.0	OVT	20, 25, 30
	B	M_{CHF}= 1.4, 1.2, 1.0	IVT	20, 25, 30
	C	Δp from PHTS	All	-
	D	v_{max}= 16, 12, 10m/s	OVT	-
	E	v_{max}= 16, 12, 10m/s	IVT	-
	F	ΔT_{sat}=20°C	All	-
	G	T_{max}=300°C	OVT CuCrZr	10
	H	T_{max}=300°C	IVT CuCrZr	10
	I	T_{max}=450°C	OVT CuCrZr	20, 25, 30
	J	T_{max}=450°C	IVT CuCrZr	20, 25, 30
	K	T_{max}=3422°C	OVT W	20, 25, 30
	L	T_{max}=3422°C	IVT W	20, 25, 30
	M	T_{max}=885°C	OVT Cu	20, 25, 30
	N	T_{max}=885°C	IVT Cu	20, 25, 30

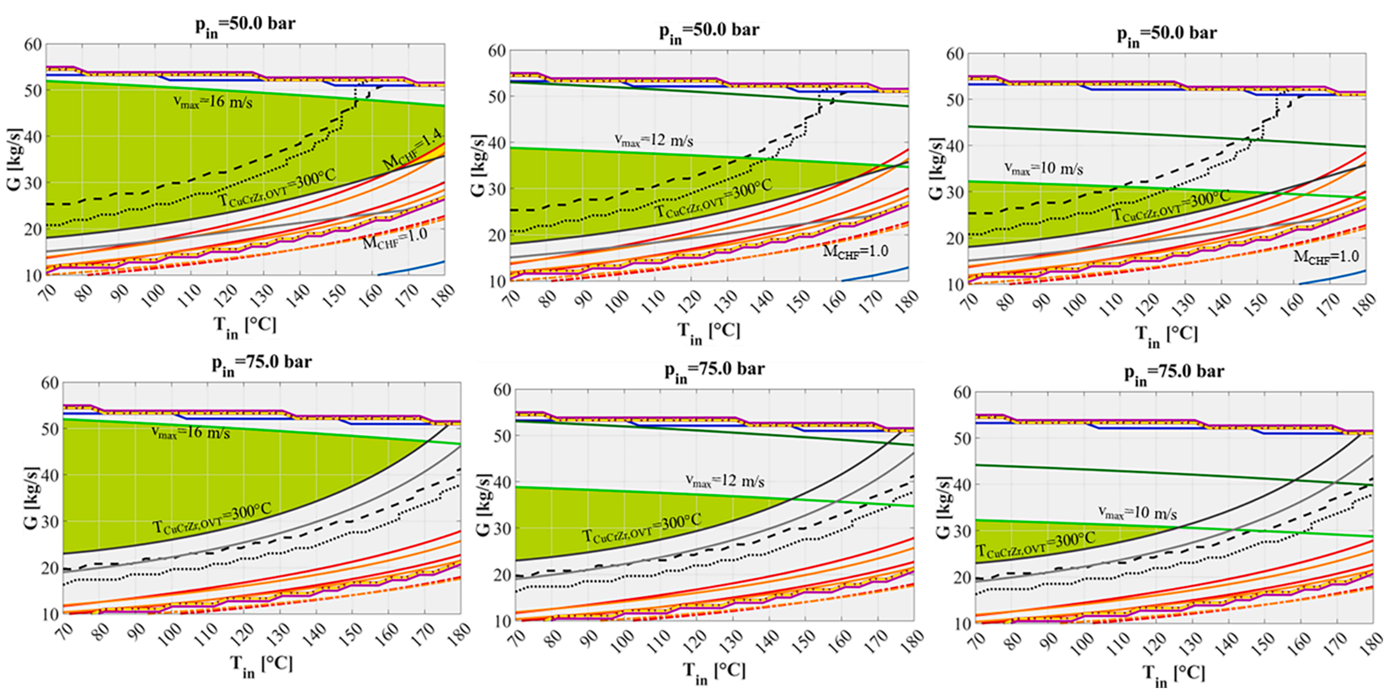

Fig. 7. Map of divertor (VTs in series) cooling circuit operating conditions for a maximum plasma heat flux of 10 MW/m^2.

in compliance with all the design criteria and with a CHF margin higher or equal to 1.4 and the yellow region, the operation with a CHF margin between 1.2 and 1.4.

For the 10 MW/m^2 case (Fig. 7), the calculations are intended to provide an indication of the margins achievable under normal operating conditions during flat-top, as well as to provide some indications on the coolant conditions that could be hypothetically adopted if the divertor target would always operate under this heat load scenario. The margin against the CHF is very high, and the green region of the map is limited only to high temperature and low coolant inlet pressure values by the CHF curves, while it is elsewhere bounded by the constraints on the maximum coolant axial velocity inside the PFU cooling tubes and the constraint on the maximum temperature in the CuCrZr of 300 °C, specifically for the OVT cooling tubes (dark grey curve). Additionally,

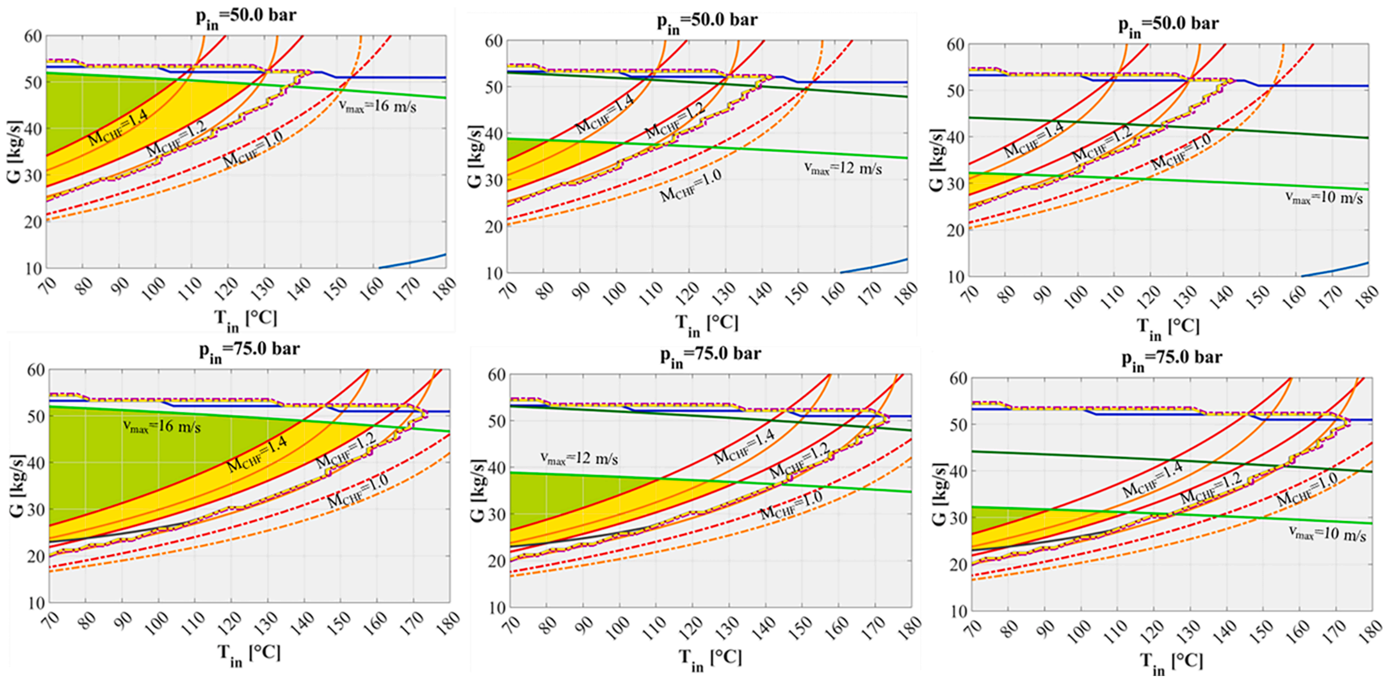

Fig. 8. Map of divertor (VTs in series) cooling circuit operating conditions for a maximum plasma heat flux of 20 MW/m^2.

occurrence of the Onset of Nucleate Boiling (ONB) in the PFU cooling channels is depicted (in Fig. 7) with a dashed black line for the OVT and a black dotted line for the IVT. As it may be argued from the figure, it is possible to find operating points characterized by two-phase heat transfer conditions at a coolant inlet pressure of 50 bar if high coolant inlet temperatures are selected.

For the 20 MW/m^2 case (Fig. 8), the green and yellow regions of the maps are delimited uniquely by the CHF margin at the OVT (red curve) and by the maximum axial coolant velocity inside the IVT PFU cooling tubes (light green curve). The reason is that, as the VTs are connected in series, they are fed by the same overall mass flow rate, which has to be subdivided into a smaller number of PFUs for the IVT (and thus higher fluid velocity in the single PFU) and a larger one for the OVT (thus lower velocity and consequently lower margin against the CHF). Although the IVT is fed with a coolant that is at a lower pressure and higher temperature, this does not constitute a critical issue for the circuit, as the critical target in terms of margin against CHF remains the OVT.

Should it be found that fretting and flow-induced corrosion phenomena are not critical for the component, or at least not critical with respect to the expected lifetime of the divertor, the green and yellow regions of the map would be still limited by the pressure drop curve (blue line), which is only slightly higher than the maximum velocity in the PFU cooling tubes of 16 m/s. Considering the intermediate limit value of the maximum PFU coolant axial velocity (12 m/s), at 20 MW/m^2 it is possible to operate in the green area at all the coolant inlet pressure values. The best scenario of 75 bar inlet pressure allows operating in a range of mass flow rates between 26 and 39 kg/s and a temperature lower than 112 °C for the green region, while in the yellow area at temperatures lower than 130 °C and mass flow rates in between 22 and 39 kg/s.

The results obtained by increasing the plasma heat flux to 30 MW/m^2 (Fig. 9) showed high difficulties to operate with such heat flux, due to the occurrence of tungsten melting in the OVT (the melting curve is not visible in Fig. 9, being at lower values of coolant inlet temperatures than the plot limits). Acceptable conditions at intermediate pressures (65–70 bar) are available for a very narrow range of flow rates and inlet temperatures and have therefore not been reported here, due to the very small extent of the yellow and green regions. Moreover, these regions are accessible only if a maximum coolant axial velocity of 16 m/s is

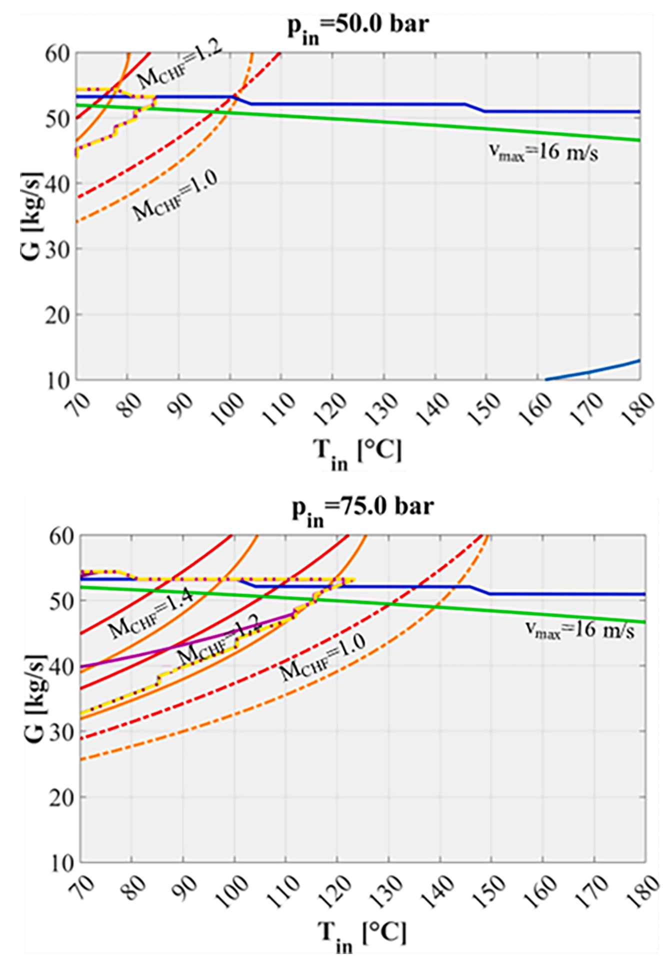

Fig. 9. Map of divertor (VTs in series) cooling circuit operating conditions for a maximum plasma heat flux of 30 MW/m^2. Only the results at 16 m/s are reported.

considered inside the PFU cooling tubes. The pumping power per cassette was also calculated. It changes significantly with the chosen coolant operating conditions, but it has an upper bound of ≈80 kW per cassette considering the axial velocity limit of 16 m/s, ≈35 kW considering the axial velocity limit of 12 m/s and ≈20 kW for an axial velocity limit of 10 m/s.

Even if the geometrical feasibility of "replaceable VTs" cooled in parallel has not been yet verified, a second parametric analysis campaign was carried out, considering the cooling circuit for the two VTs connected in parallel (as for PCD divertor design [12]) to investigate the capabilities of such cooling layout. The operating map of the VTs cooling circuit was calculated by considering the inlet coolant temperature ranging between 70 and 180 °C, the coolant mass flow rate between 25 and 150 kg/s, and the coolant inlet pressure between 50 and 75 bar.

The results obtained considering a plasma heat flux of 20 MW/m^2 are depicted in Fig. 10. In particular, a comparison with the results obtained with VTs cooled in series (Fig. 8) highlights how connecting the VTs in parallel it is possible to obtain a broadening of green and yellow areas. Considering the intermediate limit value of the maximum PFU coolant axial velocity (12 m/s), it is possible to operate at all pressure values. In particular, considering 75 bar, the area in green is in a range of mass flow rates between 43 and 82 kg/s and a temperature lower than 135 °C, while the yellow area is characterized by temperatures lower than 155 °C and mass flow rates in between 36 and 82 kg/s. The maximum coolant inlet temperatures for both green and yellow areas are increased by approximately 25 °C.

The results obtained by increasing the plasma heat flux to 30 MW/m^2 are depicted in Fig. 11. In particular, operation is allowed inside small regions, due to the occurrence of tungsten melting of the IVT. Additional analyses, not reported here for the sake of brevity, were carried out to further investigate the case of maximum coolant velocity of 12 m/s. The results obtained showed how it is possible only to operate at intermediate pressure values, i.e. between 55 and 65 bar of water inlet pressure, while considering a coolant mass flow rate between 70 and 82 kg/s and a coolant inlet temperature lower than 88 °C. Operation at lower pressures is forbidden due to the constraint on the CHF margin, while at higher pressures there is an increase in water saturation temperature, resulting in an increase of tungsten temperature leading to the monoblock melting.

Moreover, as can be easily deduced, a further increase in plasma heat flux quickly leads to the total disappearance of the yellow region due to the melting temperature constraint, and no acceptable operating condition can be found.

Furthermore, the pumping power per cassette for the "in parallel cooling" layout was also calculated. It is possible to define upper bounds for the pumping power values, equal to ≈120 kW per cassette considering the axial velocity limit of 16 m/s, ≈50 kW considering the axial velocity limit of 12 m/s and ≈30 kW for the axial velocity limit of 10 m/s, resulting higher than the corresponding upper bounds calculated for the case with the VTs connected in series.

3.2.1. Discussion on temperature level for VTs selection

Following the calculations presented in Section 3.2, the choice of operating conditions within the green region (up to 20 MW/m^2) has to be based considering the requirements listed in Section 3.1 and on several additional considerations, herewith summarized:

- It must be verified that the PFUs can withstand the thermomechanical stresses that result from the particular choice of coolant operating conditions since the presented calculations do not take into account the mechanical problem.
- An operating point characterized by low mass flow rates would be beneficial in terms of water inventory. By operating the cooling circuit with a high mass flow rate, on the contrary, it is more probable to guarantee that the loss of flow from one of the circulators of the DIV-VT PHTS may lead to a new operating point still able to guarantee at least a CHF margin higher than 1. However, this aspect could be handled differently, i.e. by increasing the number of DIV-VT PHTS circulators in parallel.
- Operating the cooling circuit with a high inlet temperature can be beneficial for the lifetime of the supporting structures of the PFUs, i.e. manifolds or target bodies. Additionally, it is known that at temperatures lower than 150 °C, irradiated CuCrZr undergoes hardening and embrittlement. This effect should be properly accounted for by performing dedicated thermo-mechanical analyses.

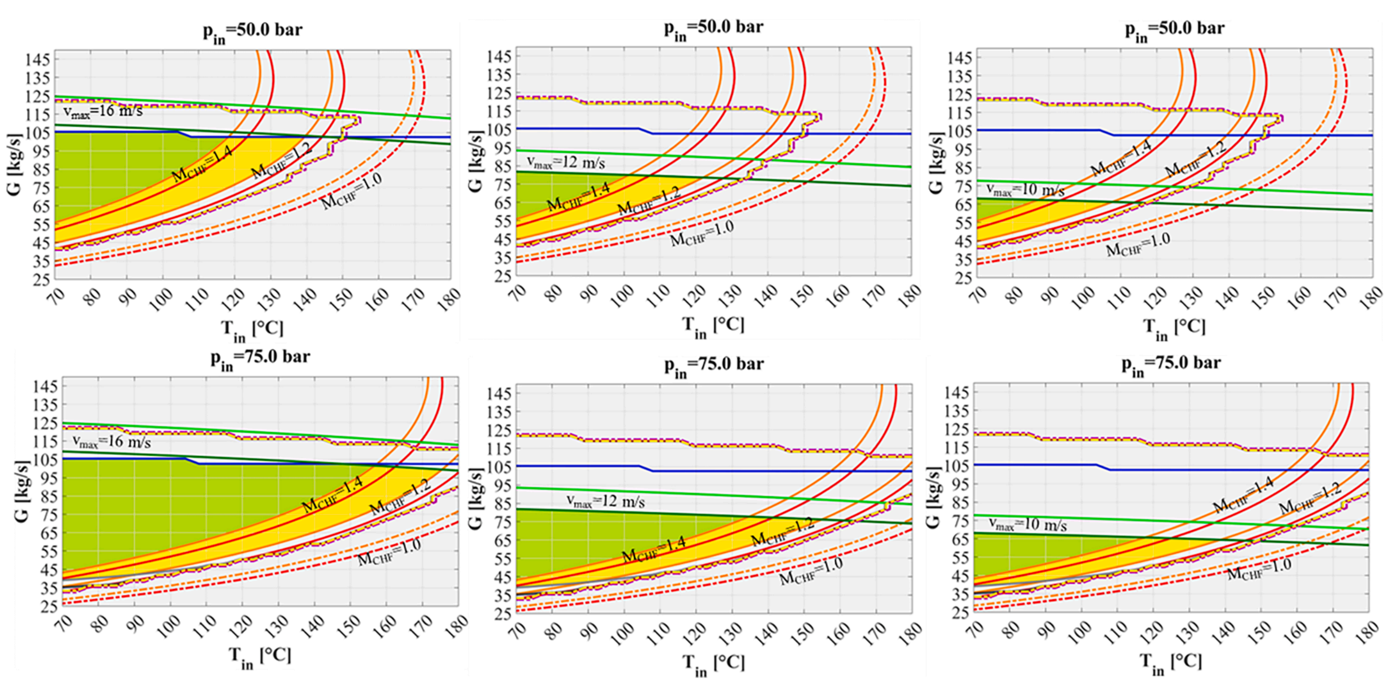

Fig. 10. Map of divertor (VTs in parallel) cooling circuit operating conditions for a maximum plasma heat flux of 20 MW/m^2.

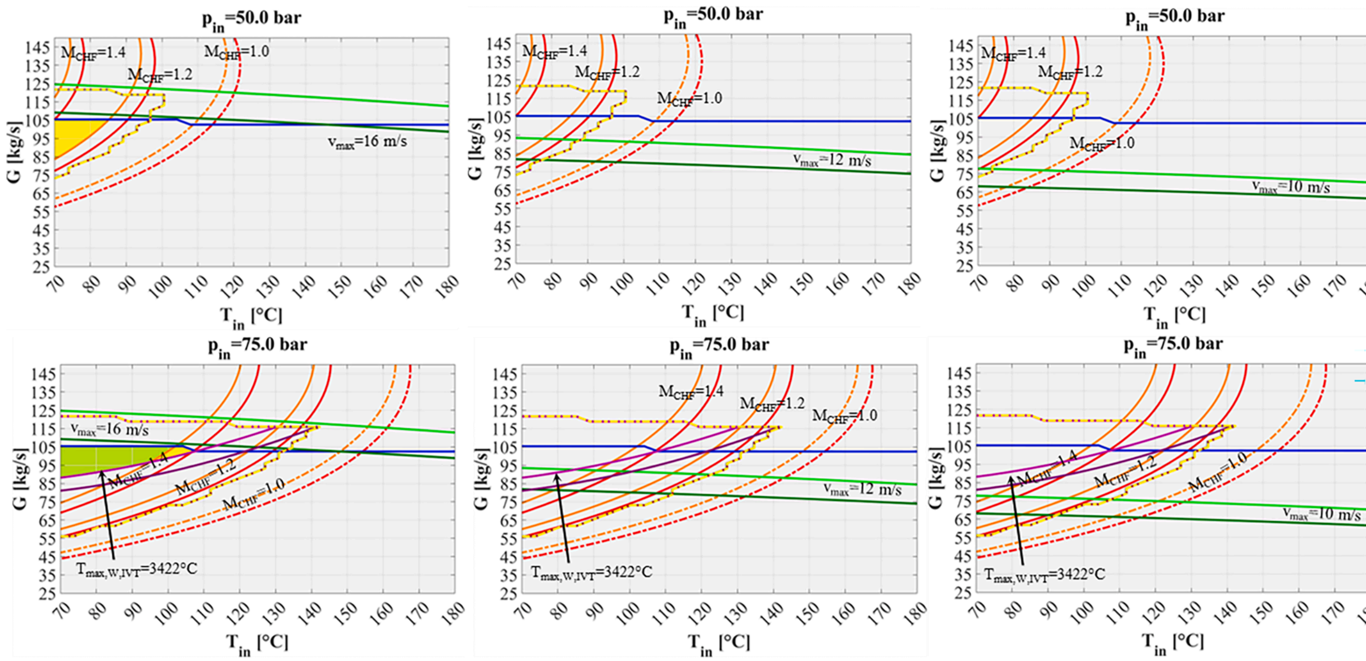

Fig. 11. Map of divertor (VTs in parallel) cooling circuit operating conditions for a maximum plasma heat flux of 30 MW/m^2.

4. Conclusion

The paper presented the activities carried out in the framework of the conceptual design phase of DEMO divertor for the identification of the temperature levels. Concerning the divertor CB, SL and the RPs, and assuming the damage level and the He production expected for the EUROFER97 structural material after 2 fpy, PWR conditions (Tin = 280 – 295 °C, Tout = 320 – 330 °C, p = 14.0 – 16.0 MPa, Δp < 0.7 MPa and G = 15 – 18 kg/s) have been selected as operating cooling condition. The following main advantages are envisaged (fulfilling functional and system requirements):

- At PWR cooling conditions the divertor cassette works in ductile range, with margin against embrittlement;
- DBTT is mainly independent from damage (dpa), making possible the extension of the divertor cassette lifetime and/or the re-use (after annealing) of the cassette for the entire DEMO lifetime;
- Temperature levels homogenized with BB with the possibility to integrate into the Power Conversion System also the power coming from the divertor cassette.

On the other side, the main concern is related to the high pressure, which requires divertor structures designed to withstand such pressure levels and relevant pipe thickness, which cutting/welding feasibility with RH tools shall be assessed. The evaluations reported in this technical note are based on the data available for EUROFER97 in irradiated conditions reported in [6], which are limited to high irradiation temperature. In future, further experiments at different irradiation temperatures would provide a complete view of the material behavior.

Regarding the VTs, the results of the parametric analysis on their cooling circuit revealed some limits on the coolant operating conditions that can be selected to guarantee the correct operation of the component, in compliance with the thermal and hydraulic constraints. The most important results are listed in the following:

- The potential occurrence of fretting and flow-assisted corrosion problems, which impose constraints on the maximum coolant velocities within the cooling tubes of the PFUs, is of fundamental importance for the extension of the operating map. As a general trend, a reduction of the maximum coolant axial velocity from 16 to 12 m/s produces a lowering of the maximum coolant temperature up to 30 °C, while a reduction from 16 to 10 m/s a lowering up to 50 °C. These values are calculated considering the average values of maximum temperature reduction for all the cases considered (both series and parallel). This significantly limits the maximum heat flow that can be safely handled by the monoblocks and forces the adoption of a lower temperature and higher pressure coolant.
- The cooling circuit in which the VTs are connected in parallel has a higher thermal performance than the circuit in which the targets are connected in series. This results in a potential reduction of the maximum coolant inlet temperature with respect to the "series arrangement" in the order of 15–25 °C, calculated considering all the coolant inlet pressure and incident heat flux values assessed.
- If the monoblocks are expected to operate at high heat fluxes (higher than 20 MW/m^2) it is mandatory to increase the coolant inlet pressure or to significantly reduce the coolant inlet temperature.
- Operation at heat fluxes of 30 MW/m^2 is limited to small regions of the operating space, due to the occurrence of tungsten melting phenomena. Adopting even higher plasma heat fluxes is most likely not possible due to the limitations imposed by melting.
- The maximum coolant pumping power is up to ≈80 kW per cassette for the configuration with VTs in series, and up to ≈120 kW for the one with targets in parallel (both cases with a maximum axial velocity of 16 m/s).
- Further thermo-mechanical analyses are mandatory to verify that the selected operating conditions are acceptable from the structural standpoint, and the proper variation of mechanical properties due to irradiation should be taken into account. A particular focus on the hardening issue of the CuCrZr when operated at temperatures below 250 °C has to be considered.

Taking into account the above-reported requirements, the following thermal-hydraulic configuration/parameters can be assumed conservatively:

- IVT and OVT connected in parallel
- Monoblock axial velocity: 12 – 16 m/s;

- Water Coolant total mass flow rate: 70 – 82 kg/s, of which about 60 % (42 – 49 kg/s) is fed to the OVT and the remaining 40 % (28 – 33 kg/s) to the IVT;
- VTs inlet temperature: 70 –88 °C for heat fluxes of 30 MW/m2, that can be extended up to 135 °C for heat fluxes of 20 MW/m^2;
- Coolant inlet pressure: 55 – 65 bar;
- VTs pressure drop: < 15 bar.

In this worst-case scenario, the margin against the CHF is reduced from 1.4 to 1.2 for both VTs. Furthermore, assuming this scenario for the determination of the thermal-hydraulic parameters to be used for the VT cooling circuit it will provide margins if the heat fluxes are below 30 MW/m^2 (e.g. between 20 and 25 MW/m^2) and much higher during the flat-top where the expected heat flux is around 10 MW/m^2.

CRediT authorship contribution statement

D. Marzullo: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **G.A. Spagnuolo:** Conceptualization, Data curation, Methodology, Project administration. **G. Aiello:** Supervision, Validation, Visualization. **J. Boscary:** Methodology, Supervision, Validation, Visualization. **G. Graziosi:** Project administration, Validation, Visualization. **I. Moscato:** Methodology, Visualization. **A. Quartararo:** Formal analysis, Investigation, Methodology. **J.H. You:** Conceptualization, Project administration, Supervision.

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.

Data availability

Data will be made available on request.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (grant agreement no 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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