WPDIV-CPR(18) 20161

G Mazzone et al.

Verification of hydraulic performance for the DEMO divertor target cooling

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.

Verification of hydraulic performance for the DEMO divertor target cooling

G. Mazzone[a], J.H. You[b], V. Cerri[a], D. Coccorese[c], S. Garitta[d], G. Di Gironimo[c], D. Marzullo[c], P. A. Di Maio[d], E. Vallone[d], A. Tincani[e], U. Bonavolontà[c], V. Imbriani[c]

[a]ENEA Frascati, Fusion & Technology for Nuclear Safety, via E. Fermi 45, 00044 Frascati, Italy
[b]Max Planck Institute of Plasma Physics, Boltzmann Str. 2, 85748 Garching, Germany
[c]CREATE/University of Naples, Industrial Engineering, Piazzale Tecchio 80, 80125 Napoli, Italy
[d]University of Palermo, Department of Energy, Information Engineering and Mathematical Models, Viale delle Scienze, 90128 Edificio 6, Palermo, Italy
[e]ENEA CR Brasimone, 40032 Camugnano (BO), Italy

Abstract. The paper presents the design activities and test of a vertical target mock-up, developed under the pre-conceptual design phase for DEMO Work Package DIV-1 "Divertor Cassette Design and Integration" - EUROfusion Power Plant Physics & Technology (PPPT) program.

The activities about the Divertor Outboard Vertical Target cooling mock-up are presented in term of CAD model, thermal-hydraulic numerical simulation, structural analysis, structural integrity verification and manufacturing procedure. Moreover, the mechanical dimensions of support systems for Plasma Facing Components (PFCs), manifold and diffuser have been analysed in detail, in order to avoid structural fault during test.

Test procedures are discussed, taking into account design parameters, design code and facility performances. The actual alloy (CuCrZr) selected for PFCs of EU DEMO divertor has been used also for the mock-up ,while two options are still under evaluation for manifolds/diffuser, CuCrZr and stainless Steel 316L(N)-IG, depending on the welding technology. Since the mock-up is mainly intended to verify hydraulic performances, it has been simplified by removing the W monoblocks from its PFCs.

Keywords: DEMO, divertor cassette, divertor target cooling mock-up.

1. Introduction

Inside the EU fusion roadmap activity Horizon 2020 [1] the pre-conceptual design activity of a Demonstration Fusion Power Reactor (DEMO) has been launched from EUROfusion Consortium. One of the main in vessel components is the divertor cassette and relative plasma facing components. Main detail can be found in [2][3].

2. Design activity for Divertor Integration

A design activity for Demo divertor has been done in the last two ears. Fig. 1 reports the DEMO assembly with the main components of a Divertor Cassette, Outer Vertical Target (OVT), Inner Vertical target (IVT), Liner, cooling tubes and Divertor-VV attaches.

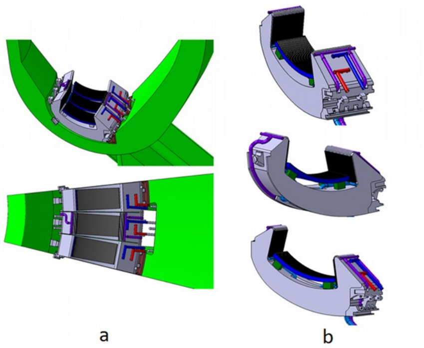


Fig. 1 DEMO divertor assembly. a) For each DEMO lower port 3 divertor cassette will be insert in the machine; b) 3d view of divertor Central cassette

The OVT has been used for the mock-up test. The first step was to prepare a detailed CAD model as illustrated in Fig. 2, the OVT Mock-up cooling circuit is obviously characterized by the same overall structure of the corresponding VT belonging to the whole PFCs. It has also been studied taking into account the presence of swirl tapes inside PFU channels. Small differences might be noticed, however, in the conformation of the diffuser and the horizontal headers, mainly due to manufacturing constraints (see Paragraph 5 Manufactory).

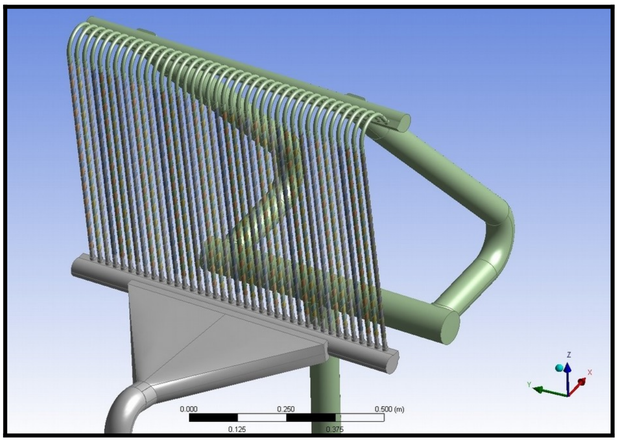


Fig. 2 – Cad model of OVT Mock-up (embedded with swirl tapes)

author's email: giuseppe.mazzone@enea.it

3. Thermo Hydraulic calculation

The results of thermal-hydraulic calculation for DEMO divertor cassette and PFC components are reported in [4],[5]and [6]. The OVT Mock-up thermal-hydraulic performances have been assessed under four different operative conditions, namely reference, alternative, room and CEF conditions (see Table 1).

Table 1. OVT Mock-up Cooling condiction.

Summary of Coolant Operative Conditions				
Parameter	Reference	Alternative	Room	CEF
Inlet Pressure [MPa]	5.0	5.0	1.0	2.4
Temperature [°C]	133	95	20	133
G per OVT [kg/s]	54.95	37.64	67.56	54.95

The results obtained indicate a pressure drop of ~0.7 MPa under reference, room and CEF condition, and of ~0.3 MPa under alternative condition.

4. Test plan

Taking into account the OVT thermal-hydraulic request and the facility parameter (see 7 Test Facility) the following test will performed:

4.1 Cold Water Flow Test

The first test requires that the prototype is flow tested at 20 °C and 2.4 MPa.

4.2 Hot Water Flow Test

The second test requires that the prototype is flow tested with a temperature that gradually reaches 130°C and p= 2.4 MPa. Possible test matrixes for the steady state tests have been summary in Table 2.

Table 2 - test matrix for OVT mock-up

RUN	TEMPERATURE	FLOW RATE			
[N°]	[°C]	[kg/s]			
1-4	20	15	25	35	55
5-8	70	15	25	35	55
9-12	100	15	25	35	55
13-16	130	15	25	35	55

4.3 Cold hydrostatic Water Test

Hydrostatic pressure test at 7.15 MPa and 20 °C will be carried out in order to:

- Verify the mechanical resistance of the components;
- Measure displacements of the mock-up components under pressure loads.

5. Manufactory procedures

Starting from the thermal-hydraulic model in Fig. 2 a detailed study of manufactory and welding procedure has been done for the principal mock-up components. Also a support system has been integrated in the final design of the mock-up. Fig. 3 shows the final CAD model, ready for manufacturing.

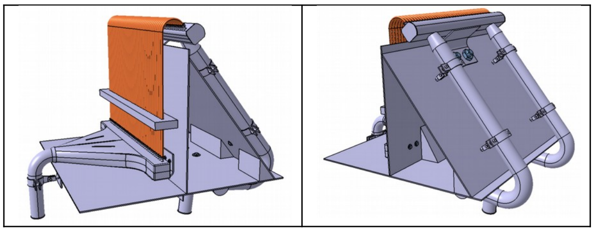


Fig. 3 - Mock-up CAD model ready for manufacturing.

The main components are:

- PF cooling tubes: are 39 tubes in CuCrZr with external diameters of 15 mm and internal diameter of 12 mm, the length of the straight part are 625.5 mm. The tubes have an internal helical swirl tape with a pitch four times the diameter (48 mm) and a thickness of 0.8 mm. It will be made of Copper and it will be 500 mm long.
- Upper Manifold: made in AISI-316L steel, it consists of two halves welded together by means of a TIG-welding (see Fig. 4). The use of two parts allows us to weld the transition joints inside the manifold, avoiding the external problem of lack of operating space due to the proximity of different PFUs.

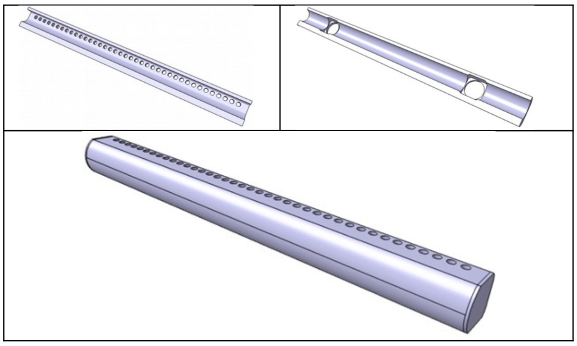


Fig. 4 Upper manifolds

- Diffuser: made in AISI-316L(N). The geometry of this component is very complicate; it was therefore thought to obtain the diffuser and the inlet manifold from a single block of steel. Obviously, the upper part and lower part will be subsequently welded (Fig. 5). The diffuser has three internal ribs only for structural integrity; the fluid-dynamic calculation [5] shows that no important changes in terms of coolant flow rate fed to the CuCrZr lateral tubes are expected.

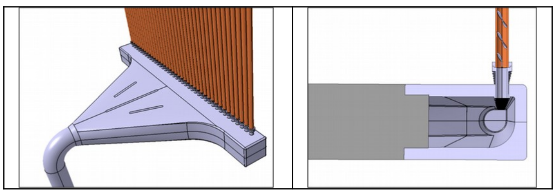


Fig. 5 Diffuser

- Transition CuCrZr /AISI 316 tubes. For the connection between the PFC CuCrZr tubes and manifold/Diffuser AISI 316 two procedures have been used and tested: a) Hot Radial Pressing (HRP) in vacuum with Cu interlayer -temperature

author's email: giuseppe.mazzone@enea.it

~ 600°C and internal pressure ~600 bar; b) Brazing in air with the use of the Lastek 31 silver alloy as filler material (Fig. 6). Both procedures have passed first pressure test with Helium at p ~ 70 bars and temperature of ~25°C. For the scope of the mock-up, it has been decided to use the brazing in air procedure because cheaper of HRP.

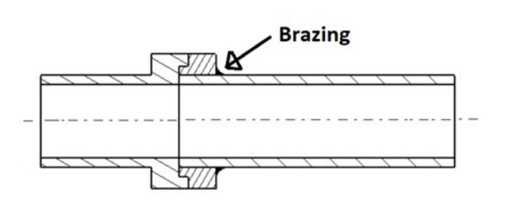
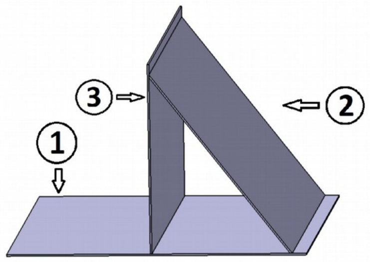


Fig. 6 Transition CuCrZr /AISI 316 tubes - Brazing in air.

- Support components as three aluminium plates (Fig. 7), Flexible Supports (Fig. 8)and Small support plates (Fig. 9).



	Length [mm]	Width [mm]	Thickness [mm]	Weight [Kg]
PLATE 1	*1060*	*1200*	*6*	*21.5*
PLATE 2	*825*	*1200*	*6*	*13.6*
PLATE 3	*765*	*1200*	*6*	*16.1*

Fig. 7 Assembly aluminium plates

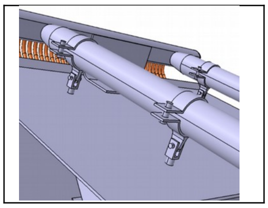


Fig. 8 Flexible support integrate on Mock-Up

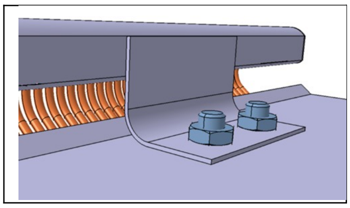


Fig. 9 Small support plates

6. Structural verification

Structural analyses have been performed on the OVT Mock-up, given the simultaneous occurrence of primary membrane stresses in the entire model and high bending stresses due to the coolant pressure on inboard wall, a survey of all options within the design rules was required to identify the inter-dependencies of the individual stress limits.

According to [7] two different type of damage shall be evaluated to prove the structural integrity of OVT Mock-up:

- P type damage
- S type damage

author's email: giuseppe.mazzone@enea.it

The elastic analysis method has been used to check the rules for prevention of both types of damage. The rules applied to prevent both the damages are compliant to Level A criteria, in case of negligible creep and negligible irradiation.

According to [8] the allowable stresses are:

AISI 316 (at 130°)=130MPa

CuCrZr (Treatment A) (at 200°)=130MPa

Both primary membrane stress and primary membrane+bending stress have been verified according to RB 3251.112 [7].

$$Pm < Sm$$

$$Pm + Pb < 1,5 * Sm$$

In case it is considered also the action of operative temperature on all bodies, the rules for prevention of secondary damages, according [7] are:

$$Pm + Pb + Q < 3 * Sm$$

The operating conditions analyzed are reported in Table 3.

Table 3 -Input of structural analyses.

Operative conditions	5 MPa	130 °C
Analysis 1	✔	-
Analysis 2	-	✔
Analysis 3	✔	✔
Test Conditions	7.5 MPa	130 °C
Analysis 4	✔	✔

The structural integrity verification following the [7] needs the linearization of the stresses along the main paths (rule RB 3324.31). The critical paths have been defined through an elastic analysis applying the most critical load scheme to the structure. In this configuration the Equivalent Von Mises Stress has been evaluated to define the region of the structure subjected to highest stress distribution. Twelve different paths have been identified as critical, their positions are shown in Fig. 10.

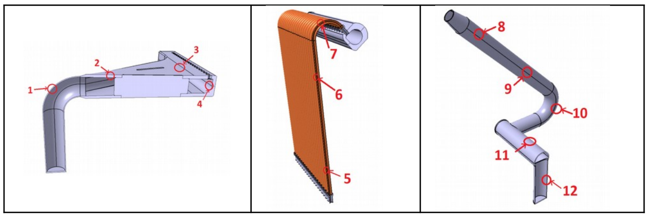
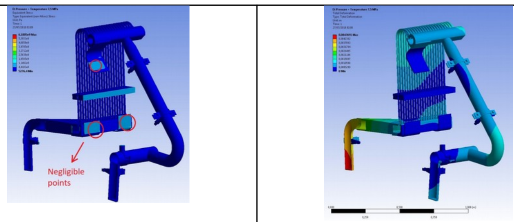


Fig. 10 - Paths for stress linearization

The results in terms of stress and displacement contours have been reported in for Analysis n°4.



EQUIVALENT STRESS (VON MISES)	DEFORMATION

Fig. 11 - Equivalent stress and deformation for Analysis n°4

In conclusion for all Mock-up components the stresses are far from the allowable limits and shouldn't cause structural problems during operative condition and test phase.

7. Test Facility

The experimental test campaign will carried out by means of the CEF 1 (Circuiti per Esperienze di Fluidodinamica) water loop at ENEA C.R. Brasimone labs [9], [10] and it will be mainly articulated in steady state tests. The facility consists of: an heat exchanger, two centrifugal pumps which can be operated in series or in parallel, the test section and the return line to the pressurized tank. The design parameters are reported in

.

Table 4 CEF design parameters

Parameter	Value	Unit
Processed fluid	Demineralized water	
Tank design pressure	0.5	MPa
Piping design pressure	2.5	MPa
Loop design temperature	140	°C
Pump max. flowrate	2 x 70	kg/s
Pump max head	2 x 1.2	MPa
Electrical heater power	2 x 60	kW
Demineralized water conductivity	< 1	µS/cm

Steady state thermal-hydraulic tests will be carried out under the DEMO-relevant range of water temperature (from RT to 130 °C) and reduced pressure (up to 2.4 MPa). During this type of tests, the total pressure drop will be determined as well as the flow-rate distribution in the PFUs.

The main instrumentation of the experimental set-up, during steady state tests, consists of:

-Two thermocouples, for the measurement of OVT inlet-outlet water temperature;

-A pressure transmitter upstream OVT;

-A Differential pressure transmitter;

-A water flow-meter type Vortex;

-Ultrasonic Flow Meter for measure the flow distribution in the 39 PFUs (see Fig. 12).

It's important a reduction of twisted tape length to obtain a reliable measure of flow rate by ultrasonic flow meter. The free length for installation should be around 10 diameters upstream and 5 downstream.

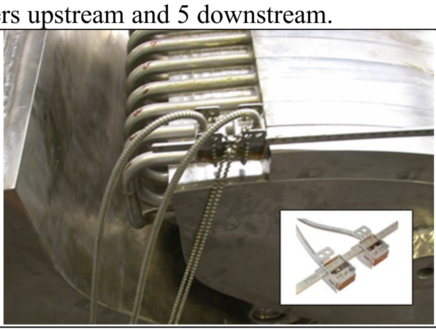


Fig. 12 Ultrasonic Flow Meter type F601 with measurement range 0,01-25 m/s.

Possible cavitation occurrence has been investigated for: Water at 2.4 MPa and 130 °C, (54.95 kg/s).

The cavitation index utilized to estimate this occurrence was defined as:

$\sigma = (Ps - Pv) / Pd$

with:

-Ps = static pressure in the cavitation zone of the component

-Pv = vapour tension in the fluid at operating temperature

-Pd = $0.5\ \rho\ V^2$ or dynamic pressure in the cavitation zone of the component

ρ = density of the fluid at operating temperature.

When $\sigma < 1$ the probability of cavitation occurrence is high. The first results have shown no cavitation insurgence.

8. Conclusion

The main activities about the preparation of a mock-up for the verification of the hydraulic performances of the DEMO divertor OVT cooling system have been presented. The design work and preliminary test of transition connection between CuCrZr and AISI 316 L tubes have been completed. The mock-up manufacture is under execution.

At the same time the CEF ENEA facility is under maintenance and update of control system to be ready in the next few months to test the mock-up.

Acknowledgments

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

References

[1] F. Romanelli, Fusion Electricity –A roadmap to the realisation of fusion energy, European Fusion Development Agreement (EFDA), 2012 -ISBN 978-3-00-040720-8.

[2] J.H. You, G. Mazzone et al., Conceptual design studies for the European DEMO divertor: Rationale and first results, Fusion Engineering and Design, Volumes 109–111, Part B, 2016,Pages 1598-1603.

[3] J.H. You, G. Mazzone et al., Progress in the initial design activities for the European DEMO divertor: Subproject "Cassette", Fusion Engineering and Design, Volume 124, 2017, Pages 364-370.

[4] P.A. Di Maio, G. Mazzone et al., Computational thermofluid-dynamic analysis of DEMO divertor cassette body cooling circuit, Fusion Engineering and Design (2018), https://doi.org/10.1016/j.fusengdes.2018.05.063

[5] P.A. Di Maio, G. Mazzone et al., On the thermal-hydraulic optimization of DEMO divertor plasma facing components cooling circuit, Fusion Engineering and Design (2018), https://doi.org/10.1016/j.fusengdes.2018.05.032

[6] P.A. Di Maio, G. Mazzone et al., Analysis of steady state thermal-hydraulic behaviour of the DEMO divertor cassette body cooling circuit, Fusion Engineering and Design 124 (2017), 437-441.

author's email: giuseppe.mazzone@enea.it

[7] RCC-MRx code, 2012 edition with 2013 1st Addendum (rule RC 5912.2).
[8] ITER SDC-IC -ITER Structural Design Criteria in-vessel components – Appendix A Materials Design Limit Data.
[9] A. Tincani et al., Steady state and transient thermal-hydraulic characterization of full-scale ITER divertor plasma facing components, Fusion Engineering and Design 83 (2008) 1034–1037.
[10] A. Tincani et al., Hydraulic characterization of the full scale divertor cassette prototype, Fusion Engineering and Design 86 (2011) 1673–1676.

author's email: giuseppe.mazzone@enea.it