

FEM and Thermal Fatigue Testing comparison of ITER-Like Divertor PFUs Mock-Ups for DEMO

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The divertor is one of the most challenging components for DEMO reactor both from the design and fabrication technology point of view, since it must be capable to withstand the high heat fluxes (HHF) expected during normal operation (up to 10 MW/m²) and slow transient events (up to 20 MW/m²), like loss of plasma detachment. Within the frame of the EUROfusion Consortium the “Target development” subproject inside the Work Package ‘Divertor’ (WPDIV) has been dedicated to achieve this performance studying different concepts.

ENEA focused on the “ITER-like” target that consists of applying the ITER design and fabrication technology to DEMO targets. The ITER-like concept mock-up was at first designed and optimized by FE analysis then manufactured and checked by non-destructive testing (NDT), finally thermal fatigue testing (TFT) and destructive testing (DT) were performed too .

This paper reports the comparison of the thermal behavior of the ITER-like mock-ups between the analysis performed using ANSYS-CFX (Computational Fluid Dynamic analysis, CFD) and the outcome of the High Heat Flux tests (HHF) made at GLADIS facility. Finally the mechanical behavior of the mock-ups has been compared in terms of ratchetting applying dedicated criteria of the ITER SDC-IC and the fatigue lifetime has been estimated by means of Low Cycle Fatigue Curves (LCFC).

Keywords: DEMO, Divertor, Plasma Facing Unit, Finite Element, Thermal Fatigue testing.

1. Introduction

ENEA that is involved in the R&D activities of the Work Package ‘Divertor’ [1], designed and optimized the ITER-like target concept according to monoblock design (rectangular tungsten blocks as armor, with a pure cast of soft Cu interlayer that are joined onto an actively cooled substrate, the heat sink, made of precipitation hardened copper alloy CuCrZr). The outcomes of this design together with first manufactured trials and High Heat Flux tests (HHFTs) showed that the reduced W monoblok dimensions had a structural impact on the failure behavior of these components [2].

The object of this work is to make a comparison between the mechanical elastic rules applied to the target mock-ups and the outcomes of the HHF tests, despite elastic criterions are generally known to be very conservative. Also the fatigue lifetime of CuCrZr heat sink pipe has been evaluated by means of the Low Cycle Fatigue Curves (LCFC).

In the case of DEMO reactor, the peak surface heat flux is expected to reach up to 10 MW/m² during normal operation and 20 MW/m² during slow transient events like loss of plasma detachment (same as ITER). Only the results for the 20MW/m² case will be considered because the loading at 10MW/m² turned out to be uncritical both in thermal and structural point of view [4].

2. PFC mock-ups and HHF tests

Three ITER-like mock-ups [4] (named DEMO05, DEMO07 and DEMO08) were manufactured by ENEA using the Hot Radial Pressing process [5], using IG CuCrZr tubes by KME DE company and two different monoblock types: one supplied by ALMT company with the Cu OFHC interlayer casting of 0.5mm made by ENEA and two supplied by AT&M company with the Cu interlayer 1mm thick made by Hipping process. The ALMT monoblocks have dimensions 22x23x4mm³ while the AT&M monoblocks have dimensions 23x25x4mm³. All mock-ups have a CuCrZr pipe with $\Phi_{in,out}$ 12-15mm. The mock-up DEMO05 was manufactured with ALMT monoblocks, while DEMO07 and 08 with AT&M ones.

The quality of joining process was assessed by non-destructive testing (NDT) performing ultrasonic technique (UT) in ENEA facility and thermography test in CEA (SATIR facility, [6]): both analysis showed the good quality of joining.

The NDT qualified mock-ups with a swirl tape (ratio of two and thickness of 0.8mm) inside to promote turbulence were delivered to IPP GLADIS facility for the thermal fatigue testing [7]. For the test the mock-ups were placed in a vacuum chamber, actively cooled with pressurized water. For the surface temperature measurements an Infrared (IR) camera and two pyrometer were used [8], while calorimeters measured the water temperature increase to estimate the entrance heat flux.

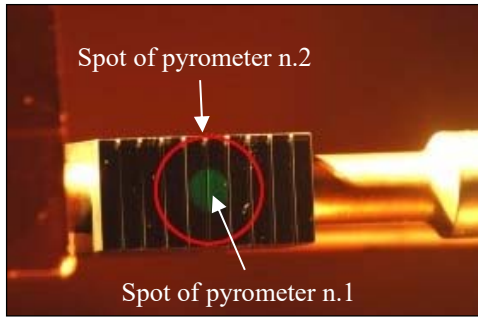


Fig. 1 Pyrometers spots on ITER-like mock-up

The mock-up #05 was tested with thermal fatigue at 20MW/m^2 (100 cycles, 10s loading on followed by 50s cooling down) after a first screening at 20MW/m^2 and 100cycles at 10MW/m^2 [9].

The inlet cooling conditions were near the expected DEMO divertor operation: 16m/s water velocity, 130°C and 4MPa static pressure.

3. Finite Element Analysis

The thermal and mechanical analyses were performed using the finite element (FE) code ANSYS WORKBENCH 18.1 on a 3D model, having the same geometry and material of the divertor mock-up #05 tested.

The thermal-mechanical analysis was performed importing the heat transfer coefficient (HTC) calculated by means of the CFD software ANSYS-CFX, thus allowing to consider the local behavior and to determine a more realistic temperature map in the components (see Fig. 2). This distribution is not uniform due to the swirl pipe effect. A stationary and uniformly distribute thermal load of 20MW/m^2 on the monoblok surface, which is 7mm from the water, was applied.

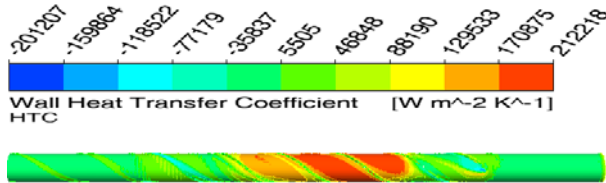


Fig. 2 HTC distribution.

Two different mechanical simulations were performed:

1. to assess the structural heat sink pipe respect to progressive deformation or ratchetting, applying the SDC-IC. In this analysis the CuCrZr and the tungsten were considered as elastic material while the Cu-OFHC was considered as elastic-plastic (Chaboche model);
2. to calculate the equivalent total strains in the pipe in order to evaluate its fatigue lifetime using the experimental Low Cycle Fatigue Curves (LCFC). In this second analysis the CuCrZr was considered as elastic-plastic too (Chaboche model).

The temperature dependence of the material properties [10] were taken into account, while the time-dependent effects were not currently included.

3.1 Thermal analysis

The CFD analysis, was used to calculate the thermal field. A preliminary convergence analysis, not reported here, was carried out to optimize the CFD mesh and to confirm the choice of performing a steady state analysis instead of a transient one. The Shear Stress Transport [11] model was used for turbulence modeling. The results were compared with the experimental data obtained from the testing carried out in the GLADIS facility.

The temperature distribution was calculated (using ANSYS-CFX 18.1) at the same hydraulic conditions of the tested mock-up, neglecting the boiling effect.

The Fig. 3 shows the maximum temperature of 1651°C on the Tungsten monoblocks which is higher than the W recrystallization temperature of 1300°C .

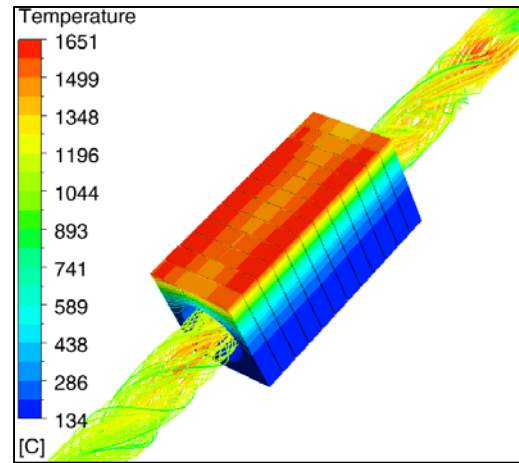


Fig. 3 Tungsten temperature distribution.

The Fig. 4 shows the thermal map of the coolant water and it points out that the temperatures were above the water critical temperature at 4MPa (250.4°C) in a wide area subjected to the maximum heat flux (thus water reached boiling regime).

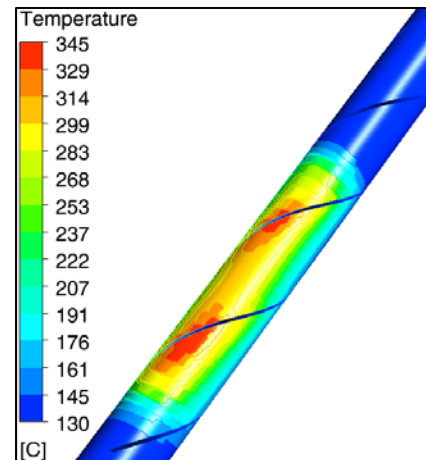


Fig. 4 Water temperature distribution.

The Fig. 5 shows that the local peak heat flux at the cooling tube wall (at 20MW/m^2) is 32MW/m^2 while the

estimated CHF is 46.3MW/m^2 . The CHF was evaluated using the modified Tong correlation proposed by Schlosser, as for ITER divertor.

The margin to the CHF is 1.45 (specified minimum margin: 1.4). A safety margin of 1.3 was fixed for the GLADIS facility that allows to reach 35.6MW/m^2 at the cooling tube corresponding to 23MW/m^2 on the W monoblock surface).

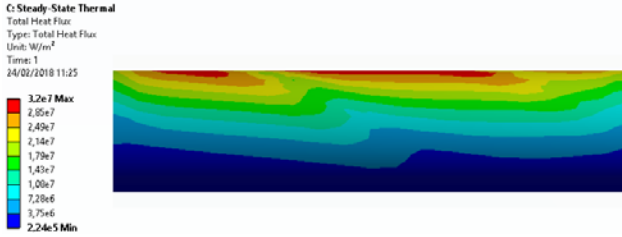


Fig. 5 Wall heat flux of the cooling tube at 20 MW/m².

The next picture (see Fig. 6) shows the temperature map for the Cu-OFHC interlayer and CuCrZr tube; maximum temperatures of 490°C and 454°C , were found respectively. The max temperature for the CuCrZr pipe was too high both for the maximum allowed service temperature $< 350^\circ\text{C}$ [10] and the max temperature limit against irradiation creep $< 300^\circ\text{C}$ [10].

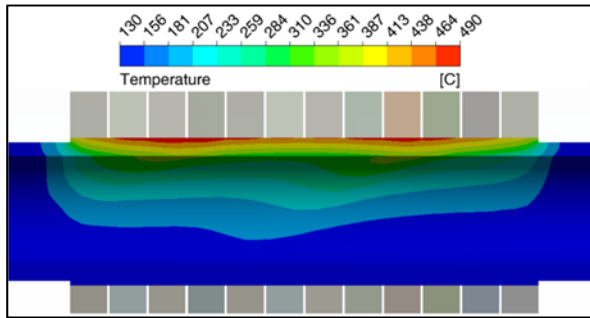


Fig. 6 Temperature radial distribution for Cu-OFHC and CuCrZr.

Fig. 7 shows the temperature measured by pyrometers on the W during 100cycles, T-KLEIB reported an average value of 1709°C , while T-QKTRD reported an average value of 1667°C : the two pyrometers average value was 1688°C . This value is in a good agreement with Ansys calculation that reported a maximum value of 1651°C (see Fig. 3).

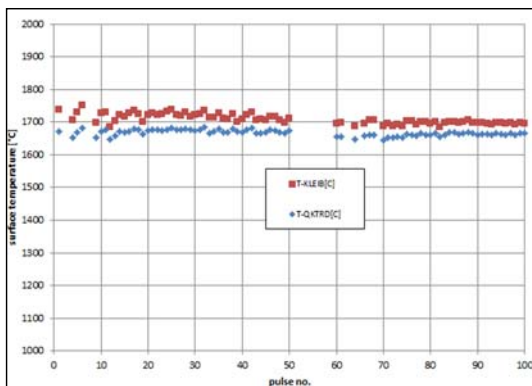


Fig. 7 Temperatures measured on the W by pyrometers during 100cycles at 20MW/m^2 .

The pictures acquired from cameras during HHF tests showed that no indication of degradation or cracks appeared during the cycling at 20MW/m^2 (see Fig. 8) even if the maximum temperature exceeds the W recrystallization temperature (1300°C).

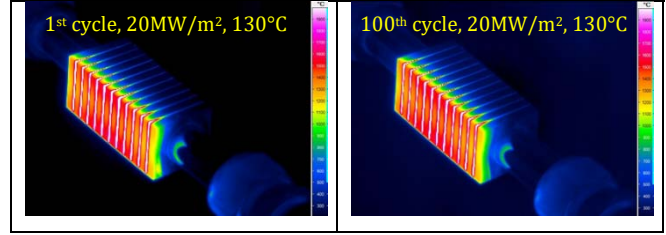


Fig. 8 HHFTs cycling at 20MW/m^2 .

3.2 Mechanical analysis

The mechanical analysis was carried out applying the temperature distributions calculated by ANSYS-Thermal as loads (water pressure of 4MPa was also considered). A steady state analysis was performed with the following boundary conditions applied: the ends of the tube were fixed like a simply supported beam (this boundary conditions are the same of the constraints during the HHF tests).

3.2.1 Ratchetting assessment

Three distinct component thermal load cases have been introduced to evaluate the ratchetting failure risk [13]:

1. From Shutdown to standby (300 cycles)
2. From Shutdown to plasma heat load (300 cycles)
3. From Standby to plasma heat load (6.000 cycles)

The Shutdown case represents the mock-up state at the environment temperature while the standby case is when the water inside mock-up reaches the expected DEMO divertor operation till heat load is applied.

The ratchetting criterion or 3Sm rule is that listed in the SDC-IC:

$$\text{Max}(\overline{Pl} + \overline{Pb}) + \overline{\Delta Q} \leq 3Sm$$

where \overline{Pl} , \overline{Pb} , $\overline{\Delta Q}$ and Sm indicates the local primary membrane equivalent stress, primary bending equivalent stress, range of secondary stress and design stress Sm .

The following picture illustrates the supporting line segments used to perform the stress linearization.

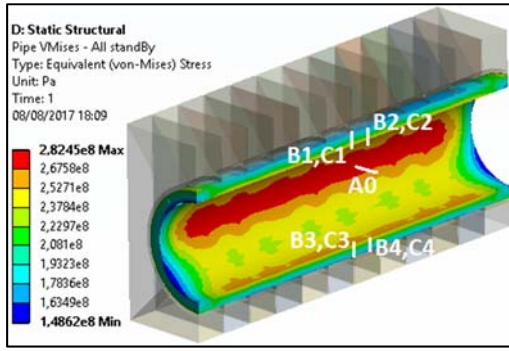


Fig. 9 Linearization paths on CuCrZr pipe.

Table 1. Ratchetting failure risk assessment results based on the 3 Sm design criterion.

Reserve factors based on max path temperature and max path P+Q							
load case	Path	Temp. Mean (°C)	3Sm Un-Irr (MPa)	3Sm Irr (MPa)	P+Q (MPa)	Reserve Factor Un-Irr	Reserve Factor Irr
Shutdown to Standby	A0	196	403	N/A	271	1.49	N/A
Shutdown to PlasmaQ	B1	369	333	N/A	425	<u>0.78</u>	N/A
	B2	372	331	N/A	415	<u>0.80</u>	N/A
	B3	141	428	N/A	322	1.33	N/A
	B4	140	428	N/A	335	1.28	N/A
Standby to PlasmaQ	C1	369	333	200	250	1.33	1.33
	C2	372	331	194	243	1.36	1.36
	C3	141	428	428	113	3.79	3.79
	C4	140	428	428	117	3.66	3.66

3.2.2 Fatigue life estimation

The fatigue life estimation for the CuCrZr heat sink pipe can be evaluated using the experimental LCFC [10]. These curves are available in a temperature range between 22°C and 350°C, while it was noted that the CuCrZr pipe reaches a maximum temperature of 457°C (see Fig. 6).

The mechanical analysis performed with the CuCrZr as elastic-plastic material showed that the highest value of 0.7% for the strain range on the pipe was found at the second thermal load case when the mock-up goes from the plasma operation (up to 454°C) to the shutdown state (22°C) (see Fig. 10).

Two hot spots are visible on the top pipe surface due to the swirl pipe effect (see also the HTC distribution, Fig. 2).

The Table 1 shows that the value of stress intensity for cyclic loads (progressive deformation or ratchetting) exceeds the allowable limit at path B1 and B2 for an heat flux of 20MW/m², but it is noted that the elastic criterion is generally known to be conservative. Moreover the tested mock-up showed no cracks or defects after the 100cycles at 20MW/m².

This worst case does not correspond to the HHF test condition for which we consider the third thermal load case when the mock-up goes from the plasma operation (up to 454°C) to the standby state (150°C) (see Fig. 10). This case showed a total strain range value of ~0.6%.

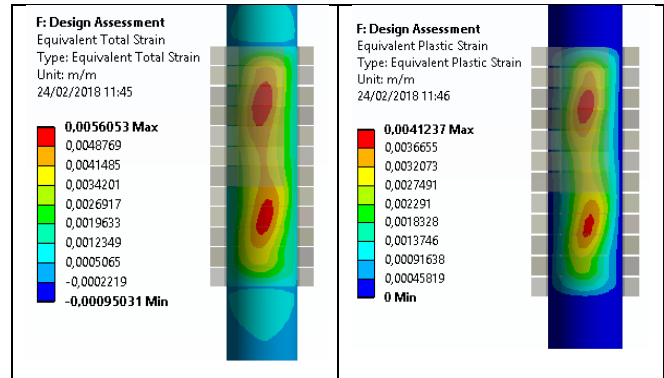


Fig. 11 Total and plastic strain range for the Standby to Plasma Heat load case.

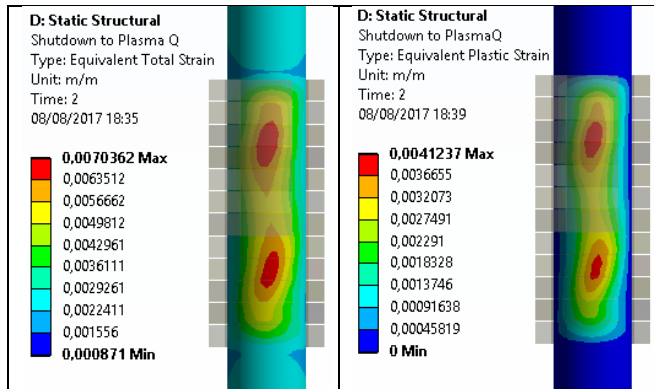


Fig. 10 Total and plastic strain range for the Shutdown to Plasma Heat load case.

The Fig. 12 shows the fitting curves for the high, intermediate and low strength Copper alloys. Also a fitting of all data is reported together with the fatigue design curve obtained in the following way: making a division by 2 of the strain range and a division by 20 of the number of cycles (the two curves resulting forms together an endurance design limit).

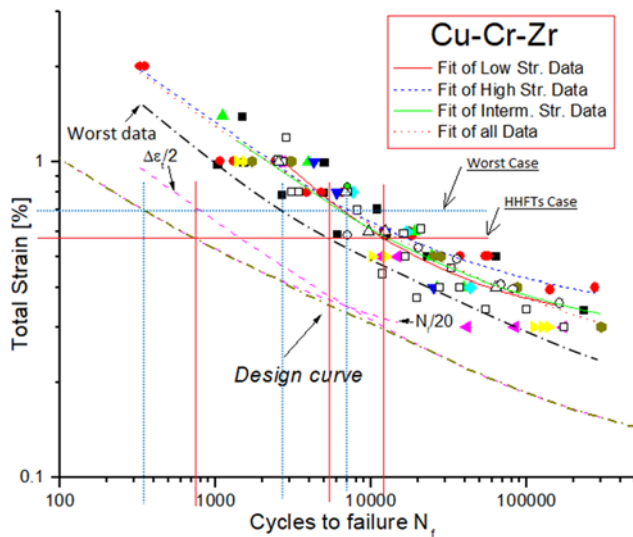


Fig. 12 LCFC for CuCrZr (fitting data and design curve).

The fitting curve of all data (20°C-350°C) gives for the highest strain range value of 0.7% (conservative case) a number of cycles of 7000. Shifting this curve towards the worst data we can find a number of cycles of around 3000. Assuming the design fatigue curve as representative of the highest calculated temperature a number of cycles between 300 and 400 can be found (see Fig. 12).

The thermal load case corresponding to the HHF test condition gives at the strain range of ~0.6% the following three number of cycles: ~730, ~5300 and ~10k.

The number of cycles coming out from the most conservative case and from real one are higher than the 300 cycles foreseen at 20MW/m². These whole results are in accordance with the current test outcomes that showed the mock-up surviving 100cycles at 20MW/m² with no defects.

4. Conclusions

The comparison between the FE analysis of the mock-up and the outcomes of the HHFTs performed at IPP GLADIS facility showed that:

1. 3Sm rule is not passed at two locations but elastic criterion is generally known to be conservative;
2. Fatigue life estimation ensure the 300 cycles foreseen at 20MW/m².

The ITER-like mock-up #05 survived 100cycles at 20MW/m² showing the high quality of fabrication and robust design concept (the possibility to reach 300cycles is currently under cost investigation). Moreover UT and DT after HHF tests are foreseen together with the CuCrZr mechanical characterization at high temperatures.

Acknowledgments

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