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Helium-cooled divertor for DEMO: Manufacture and high heat flux tests of tungsten-based mock-ups

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ABSTRACT

A helium-cooled divertor concept for DEMO has been investigated extensively at the Forschungszentrum Karlsruhe under the EU power plant conceptual study, the goal being to demonstrate performance under heat flux of 10 MW/m^2 at least. Work covers different areas ranging from conceptual design to analysis, materials and fabrication issues to experiments. Meanwhile, the He-cooled modular divertor concept with jet cooling (HEMJ) has been proposed as reference design. In cooperation with the Efremov Institute, manufacture and high heat flux testing of divertor elements was performed for design verification and proof-of-principle. This paper focuses on the technological study of the fabrication of mock-ups from W/W alloy and Eurofer steel supporting structure material. The high heat flux test results of 2006 and 2007 are summarised and discussed.

1. Introduction

Under the framework of the EU power plant conceptual study, a helium (He) cooled tungsten (W) modular divertor concept [1] is being investigated with a goal of handling a high heat flux of at least 10 MW/m^2. The W module is based on a modular arrangement of He-cooled fingers (Fig. 1) for reduction of thermal stresses. Each finger consists of a W tile acting as a thermal shield and a sacrificial layer at the same time which is brazed to a thimble made of W alloy, i.e., W–1%La_2O_3 (WL10), which functions as a pressure carrying heat exchanger. The finger module is cooled by 10 MPa He at 600 °C inlet temperature at a nominal mass flow rate (mfr) of 6.8 g/s per finger. Design verification and proof-of-principle experiments are regarded indispensable elements in the development of a reliable divertor concept. For this purpose, a combined facility (Fig. 2) consisting of the TSEFEY electron beam facility (60 kW at 27 keV beam energy) and a new moveable He loop (10 MPa, 600 °C) has been built at the Efremov Institute, St. Petersburg, Russia, under cooperation with Forschungszentrum Karlsruhe. In this paper, the fabrication steps of the module and recent high heat flux test results as well as the reference design are summarised.

2. The reference design

Two promising modular concepts HEMS (He-cooled modular divertor with slot array) and HEMJ (He-cooled modular divertor with multiple-jet cooling) have been investigated [1]. The HEMS is based on the use of a flow promoter in form of a slot array while the HEMJ relies on the principle of multiple-jet impingement cooling. Meanwhile, the HEMJ has been defined as reference (Fig. 3) because of its simpler design and cost-effective production route. Both concepts use small hexagonal W tiles (18 mm width over flat) are used as a thermal shield and a sacrificial layer (5 mm thickness). They are brazed to a thimble (Ø15, 1 mm thick wall) made of WL10, thus forming a cooling finger, which is connected to the supporting structure made of oxide dispersion strengthened (ODS) steel. To compensate the large mismatch in the thermal expansion coefficients of W and steel a transition piece is needed. The current transition piece design uses Cu casting with conical interlock (optionally, Co brazing). For HEMJ, a steel cartridge carrying the jet holes is placed concentrically inside the thimble. The number, size, and arrangement of the jet holes, as well as the jet-to-wall distance are important parameters. With the support of the computational fluid dynamic (CFD) analyses [2] the following geometry was found suitable: 24 holes Ø0.6 mm and 1 center hole Ø1 mm, jet-to-wall spacing 0.9 mm resulting in a maximum tile and thimble temperatures of about 1700 °C and 1170 °C, respectively, and a pressure loss (Δp) of 0.13 MPa, under nominal design conditions (10 MW/m^2, 6.8 g/s mfr).

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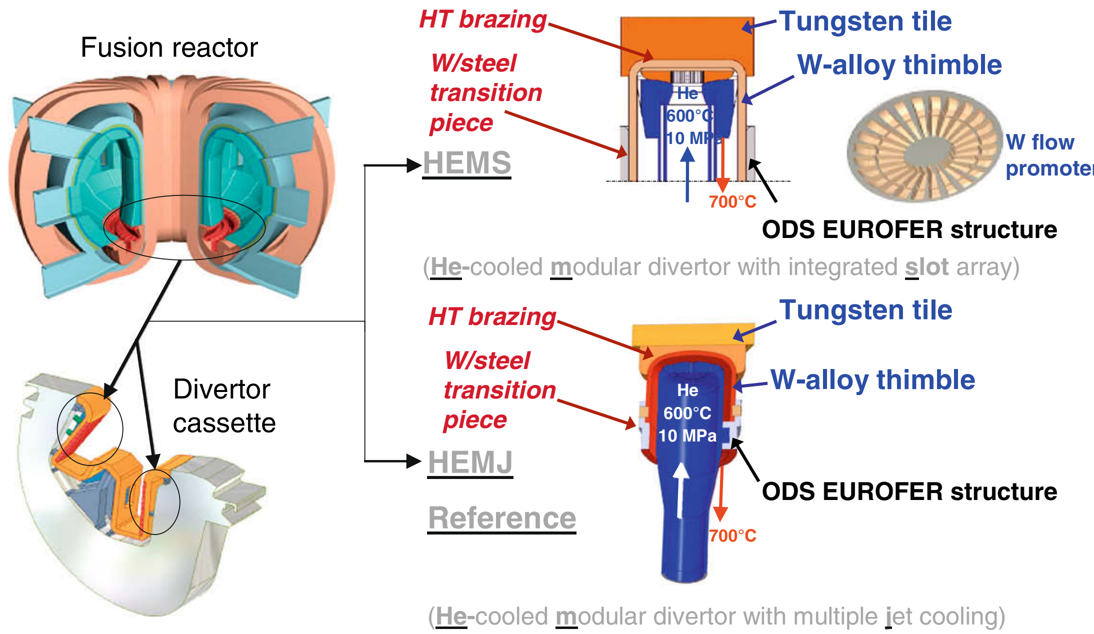

Fig. 1. The He-cooled modular divertor designs HEMJ and HEMS.

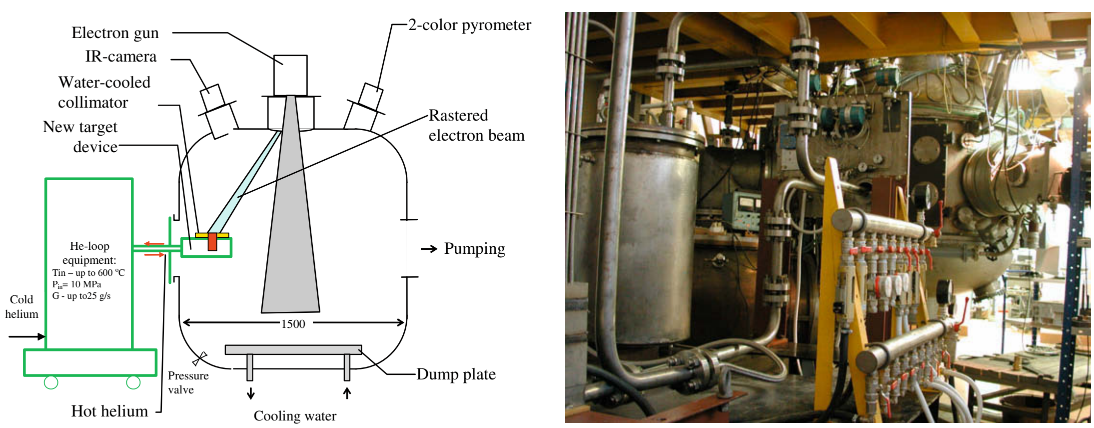

Fig. 2. The combined He loop and TSEFEY testing facility at Efremov.

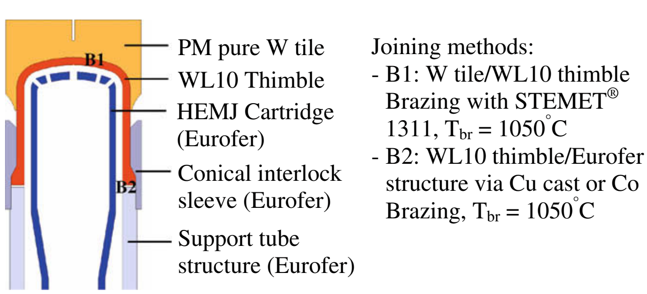

Fig. 3. HEMJ mock-up definition for HHF tests.

3. Mock-up manufacturing and the combined test facility

Based on the knowledge gained from the preceded technological investigations [3,4], the reference W mock-up was defined for the high heat flux tests (Fig. 3). The HEMJ jet cartridge and the holding structure of the mock-ups are made of Eurofer which differs from the designated ODS Eurofer material. For the W/WL10 joint the brazing material STEMET® 1311 (brazing temperature (T_{br} = 1050 °C) was used. Besides the copper cast joining method, the 71KHCP (Cobalt (Co)-based) brazing filler metal (T_{br} = 1050 °C) was applied at the W-steel transition joint of certain mock-ups. Castellated and non-castellated W tiles were investigated. In the first test series in 2006 six 1-finger mock-ups, five of HEMJ and one of HEMS type, were fabricated in following steps: (a) machining of external surface of the WL10 thimble, Eurofer cylindrical ring, internal surface of the pure W tile, (b) brazing of W thimble to cylindrical ring and W thimble to W tile, (c) final machining of the internal surface of the W thimble and the outer shape the tile. All tiles of the mock-ups were made of Russian W with the exception of the mock-up #1, its tile being made of Plansee W grade. All thimble parts are made of Plansee WL10 material. As an alternative to the W/Eurofer joint by cast copper, a brazed W/Eurofer joint using Co-based filler metal was considered for mock-up manufacture (mock-ups #5/HEMJ and #6/HEMS). For high heat flux (HHF) testing of the mock-ups, a special target holder was designed and manufactured. This target holder consists of two main parts, the manifold device and the water-cooled shielded mask which has a hexagon-shaped frame made of Mo alloy TZM.

A He loop was designed for a combined operation with the TSEFEY facility. It enables mock-up testing at a nominal He inlet temperature ($T_{He,\ in}$) of 600 °C, an internal pressure of 10 MPa, and a pressure drop in the mock-up of up to 0.5 MPa. The main He loop units are placed on a moveable vehicle on railways (Fig. 2, right). In the first stage of the He loop a stationary mass flow rate of 24 g/s was achieved by means of an oil-free membrane compressor.

4. The high heat flux experiments

The first experiment series performed in 2006 covered six mock-ups (five of HEMJ and one of HEMS types). The mock-ups were tested within an HHF range of 5–13 MW/m^2. The heat flux is determined via the heat power absorbed in the He loop. The He cooling parameters are 10 MPa inlet pressure, ~500–600 °C inlet temperature, and a varying mass flow rate in the range of ~5–15 g/s. The thermocyclic loading was simulated by means of switching the beam on and off (30/60 s as default cycle). The experimental results of this first testing campaign are reported in detail in [1]. Altogether, it can be said that the performance of the He-cooled divertor concepts (HEMJ and HEMS) of 10 MW/m^2 was already demonstrated by the first experiment series. The results of destructive post-examinations revealed that W parts of these mock-ups and the thimble contain pre-existing defect, presumably by micro-cracks initiated during the fabrication processes. Nevertheless, sudden destruction and/or completely broken mock-ups, i.e., no brittle failure were not observed. No recrystallisation of W thimble was observed in any mock-up. The measured pressure losses were regarded optimistic compared to the calculated value (~50% overestimation). Four additional HEMJ mock-ups were fabricated, however, cracking occurred in the tiles of all four mock-ups during the brazing of the W tiles (W rod material from Plansee) with the thimbles. Therefore, these mock-ups were not brought to HHF tests.

For the following test series in 2007 technological/technical improvements have been made: (a) the mock-up geometry was optimised to reduce the thermal stresses by means of finite element analyses (Fig. 4, #17 and 18), (b) new target device for

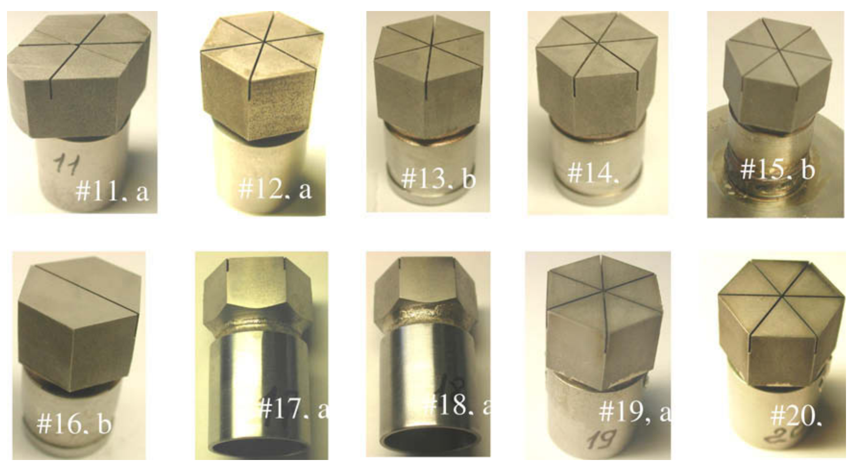

Fig. 4. 1-Finger HEMJ mock-ups for 2007 HHF tests. Tile material: rod (Plansee, vertical grain orientation), regular machining of tile and thimble (turning and grinding). Thimble/conic sleeve joining: (a) Co brazing (71KHCP, 1050 °C), (b) Cu casting (1100 °C).

Table 1
2007 HHF experiments on 1-finger HEMJ mock-ups.

Mock-up number	Cycle number at heat flux (MW/m^2)/(beam on/off)*	mfr (g/s)	T_{He} in/out (°C)	Δp (MPa) at mfr
12 (d)	18 at 10; (→ gas leak at the central upper area of the tile, no significant visible damages)	9–10	560/610	0.2
13 (c)	70 at 10; (→ gas leak at the central upper area of the tile, slight cracking of the tile top surface)	9	570/620	0.16
14 (c)	90 at 9; (→ surface temperature increasing during cycling, tile detaching, no gas leak, melting and cracking of the tile)	9	560/610	0.17
15 (c)	Gas leak appeared between tile and conic sleeve during screening tests, no visible damages	9	550/590	0.17
20 (d)	Gas leak appeared between tile and conic sleeve during screening tests, no visible damages	9	550/590	0.17
17 (d)	89 at 10; (→ experiment was terminated after detecting tile temperature increase, no gas leakage, no damages)	9	570/620	0.18
19 (d)	Gas leak between tile and conic sleeve during first heating at 450 °C and 8 MPa, cracks inside the thimble (vertical visible) and in thimble/conic sleeve brazing zone			
18 (d)	102 at 9.5/**; (→ excellent performance, no any damages, no leaks, stable surface temperature from cycle to cycle, no any visible damages)	12.5	550/590	0.33

	W tile	W-WL10 joint	WL10-Eurofer joint
(a)	Non-castellated	STEMET 1311 brazing	Cu casting in conical lock
(b)	Non-castellated	STEMET 1311 brazing	Co brazing in conical lock
(c)	Castellated	STEMET 1311 brazing	Cu casting in conical lock
(d)	Castellated	STEMET 1311 brazing	Co brazing in conical lock

Beam on–off cycles.
* Default 30/30 s.
** Soft ramp: 20 s – up, 20 s – hold, 20 s – down, 20 s – pause.

1-finger mock-ups was designed and manufactured which allows for changing the mock-ups without cutting and rewelding, and (c) additional grinding process was applied after turning the W mock-up parts. In Fig. 4 10 HEMJ mock-ups (#11–20) manufactured for the second test series in 2007 are illustrated. The mock-ups #11 and 16 were used for the metallographic analysis without HHF tests. The results of the 2007 HHF tests are summarised in Table 1. Test conditions are: 10 MPa He, at 550 °C inlet temperature, mfr = 9–13 g/s, thermal screening (thermal response) in the range of 6–10 MW/m^2 (few cycles per step), thermal cyclic tests at 10 MW/m^2 till damaging or for $n \leqslant 100$ cycles without damages. A beam on/off sharp ramp of 30/30 s was applied to all mock-ups for simulating the thermal cyclic loading, with the exception of the last test with mock-up #18, performed with a soft ramp (20 s – up, 20 s – hold, 20 s – down, 20 s – pause).

The 2007 experiments started with the mock-up #12 with a castellated W tile. Heat flux loading was applied to the mock-up surface at a constant mfr of ~9–10 g/s. The mock-up survived 18 cycles at 10 MW/m^2. Gas leak appeared at the central area of the loaded tile surface. No remarkable visible damages were detected. The following mock-up #13 with a castellated W tile survived up to 70 cycles at 9 MW/m^2 at mfr ~9 g/s, $T_{\mathrm{He,\,in}}$ ~570 °C. Slight cracking of the tile top surface with gas leak were detected. Mock-up #14 (castellated) withstood 90 cycles at 9 MW/m^2. Surface temperature increased during cycling. Finally W tile detached from the thimble, which caused further overheating and melting of the W tile. The mock-ups #15, 16, and 19 were defective at the beginning during the screening tests (gas leak failure). The mock-up #17 with the optimised tile geometry was successfully tested at 89 cycles under 10 MW/m^2. The experiment was terminated after detecting tile temperature increase, no gas leakage, no damages. The measured pressure losses at 9 g/s mfr stayed in a range of about 0.16–0.18 MPa which agreed well with the values obtained from the first test series. The tile surface temperatures of these mock-ups during the tests interpreted from infrared pictures reached at a range between 1600 and 1700 °C. The following mock-up #18 with the same geometry was subjected to the same heat load of 10 MW/m^2 but at an increased mfr of 12.5 g/s in order not to exceed the remelting temperature of the W–W joint. In addition, a soft ramp which was regarded more realistic to the DEMO condition was applied in this test at the same time. This mock-up outstandingly withstood 102 thermal cycles without any damages.

5. Conclusions and outlook

The current step of work is aimed at the high heat flux tests of divertor mock-ups to demonstrate their fabricability and their performances. In cooperation with the Efremov Institute, a combined electron beam and He loop facility was built. Comprehensive technological studies were performed on W/W and W/steel joining of the divertor parts. First mock-up series were successfully fabricated and HHF tested in 2006. The 2006 results already confirmed performance of the divertor module under 10 MW/m^2. For the second test series in 2007 the mock-ups were further improved in view of thermal stress reduction as well as the manufacturing quality of the parts. This brought to a noticeable improvement in performance and resistance against thermal cyclic loadings. The last successfully tested mock-ups survived outstandingly more than 100 cycles under 10 MW/m^2 without any damages.

Nevertheless, it became clear that the major reasons for the high failure rate of mock-ups generally lie in: (a) base material quality, (b) manufacturing quality (W turning, jet holes drilling, EDM of W surfaces, etc.), (c) overheating of the tile/thimble brazed joint leading to detachment, and (d) induced high thermal stresses. Non-destructive testing is regarded indispensable measures for the verification/qualification of (a) and (b). A filler metal with a higher brazing temperature than that of STEMET 1311 (e.g., CuNi 44, T_{br} = 1300 °C) will be used in further tests as a measure against (c). Further design optimisation is also required in particular for the W-steel joint region with a large mismatch, where cracks were always observed in all tested mock-ups. Work on qualification of W mock-ups exposed to high heat fluxes has been launched. The evaluation results of 1-finger mock-up tests will be used as a basis for completion of the 9-finger mock-ups and their following HHF tests.

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