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Development of a helium-cooled divertor: Material choice and technological studies

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Abstract

Within the framework of the EU power plant conceptual study (PPCS), a He-cooled divertor concept has been investigated at Forschungszentrum Karlsruhe in cooperation with the Efremov Institute. The design goal is to remove a high heat load of at least 10 MW/m^2. The design is based on a modular construction of cooling finger unit that helps reduce thermal stresses. The divertor finger unit, which is cooled by high pressure helium, consists of a tungsten tile as thermal shield and sacrificial layer, and a thimble made of tungsten alloy. The success of this design depends strongly on the effectiveness of the cooling technology and on the availability of appropriate structural materials such as tungsten alloy and oxide-dispersion-strengthened (ODS) steel as well as the related fabrication and joining technology. Results of this investigation are discussed in the paper.

1. Introduction

In the divertor design tungsten is usually considered as thermal shield and sacrificial layer for plasma-facing components due to its high resistance against sputtering. For the helium-cooled divertor, the requirement of a high thermal load also implies that tungsten (or tungsten alloys) is most suitable as the structure material [1] due to its excellent thermo-physical properties: high melting point, high thermal conductivity, and low thermal expansion. Drawbacks are its high hardness and high brittleness, which make the fabrication of tungsten components relatively difficult. The current design [2] is based on the use of commercial materials and the unirradiated properties reveal that improvement of some material properties is strongly required, e.g. ductile to brittle transition temperature (DBTT) and re-crystallization temperature (RCT) of tungsten and its alloys, due to which the range of divertor operating window is limited.

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2. Major requirements and design principle

The design goal is to remove a high heat load of at least 10 MW/m^2. The lower temperature of the divertor operating temperature window is limited by the DBTT and the upper temperature by the RCT of structures made of refractory alloys under irradiation. The divertor has also to survive about 100–1000 thermal cycles between operating temperature and room temperature during operation. A modular design helps reduce thermal stresses. Two conceptual designs of a He-cooled modular divertor (Fig. 1) have been investigated. The reference version with multiple jet cooling (HEMJ) [3] and the back-up solution with a slot array (HEMS) [4] as a flow promoter which enhances convective cooling. The main design principle common to both options is the use of small tungsten tiles (about 5 mm thick) as a thermal shield and sacrificial layer which is brazed to a thimble-like structure made of tungsten alloy such as W–1%La_2O_3 (WL10), thus forming a cooling finger unit. The separation between tungsten tile and thimble is to stop the crack growth induced from the plasma-facing surface. The cooling finger units are fixed to the supporting structure made of ODS steel (e.g. an advanced ODS EUROFER or a ferritic version of it) by means of brazing and/or mechanical interlock. The divertor is cooled with helium at 10 MPa and operating between 600 °C and 700 °C (inlet/outlet temperatures).

3. Development strategy

Strategies for a successful approach to the design goal (Fig. 2) are outlined as follows: (a) thermo-hydraulic screening tests of various design and parameter variants; in parallel with investigation of W material grades, development of W joining technology (W/W and W/steel), as well as the study of fabricating W parts, (b) definition of W mock-ups from a closer selection of design options for high-heat-flux (HHF) tests in a helium loop, (c) HHF tests of W single-finger units (2005/2006), (d) HHF tests of 9-finger modules (2006/2007), (e) conceptual design of a test divertor module (TDM) to be tested in ITER beginning in 2020, and (f) HHF tests of larger components (module strips, target plates, complete ITER TDM) beginning in 2008 in a bigger helium loop to be built (e.g. the *He*lium *Lo*op *Ka*rlsruhe (HELOKA) which is in planning).

4. Design-related investigations

4.1. Choice of divertor materials

The requirement for high resistance against HHF and sputtering, high thermal conductivity, low-activation, and high strength leads to the choice of tungsten or its alloy as the most promising divertor material. In addition, the thermal conductivity of tungsten does not decrease under neutron irradiation

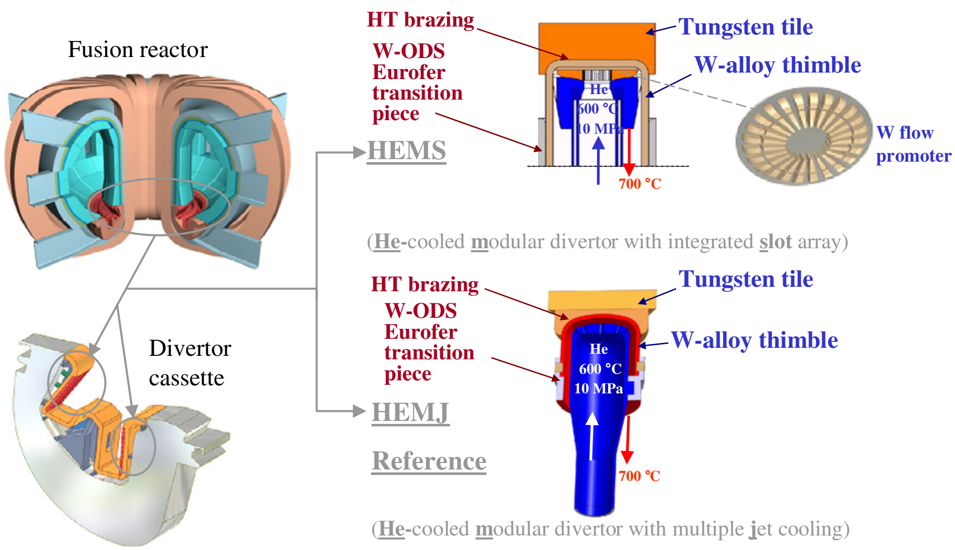

Fig. 1. The He-cooled modular divertor designs: HEMJ (reference) based on multiple jet cooling and HEMS (backup) using slot array as a flow promoter.

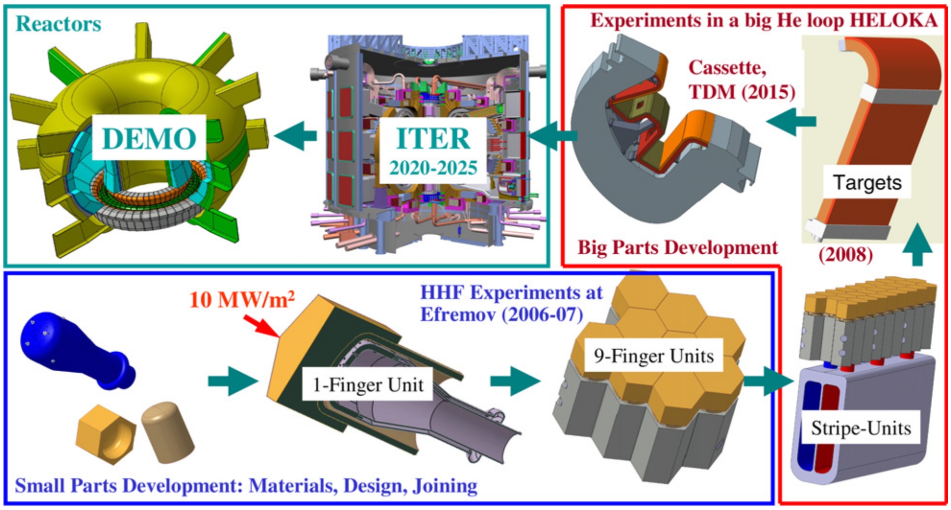

Fig. 2. Strategy and roadmap for the divertor development.

appreciably. On the other hand, there are some disadvantages with tungsten: (a) Its high hardness and high brittleness will make the manufacturing of divertor components more difficult, and (b) its poor values of DBTT and RCT will strongly restrict the design temperature window when used as divertor structures. This temperature window and the ductility can be increased by adding fine oxide particles (ODS tungsten), with alloy WL10 being regarded the most suitable option for the divertor design. The DBTT and RCT of WL10 under fusion neutron irradiation are estimated to be around 600 °C and 1300 °C, respectively. This shall be taken as the 'design window' range in the following analysis. Transient events (disruptions and ELMs) have been taken into account, with a 5 mm thick sacrificial layer of the tungsten armour without any structural function being foreseen for an estimated service life of about 1–2 years based on calculations [5] and experiments [6] for ITER. The transmutation rate of W to Re is given in [7] at about 0.2 at.% per dpa, leading to approx. 8 at.% expected at 40 dpa. Due to the relatively high level of decay heat in tungsten, the divertor has to be cooled actively for some weeks after reactor shut-down before removing to the hot cells.

4.2. Fabrication of tungsten divertor parts

The results of present investigations [8] show that electrochemical milling (ECM), and powder injection moulding (PIM) [9] are promising methods for mass-production of tungsten parts. The electric discharge machining (EDM) method was found to be time-consuming and expensive for shaping of micro-structured W arrays and, thus, could be used only for screening purposes e.g. for cooling structure examination. The difficulty of the ECM method lies in the surface passivation effects which suppress current flow and stop defined local material removal. It was found in the first experiments that a certain variation of chemical, physical, and important technical parameters (electrolyte composition, pH, temperature, convection, polarisation routine) is favourable for W machining. Two approaches are being investigated more precisely at the moment. The first method is an electrochemical structuring of masked W-workpieces (M-ECM). The desired structure is printed on the W surface by means of lithographical techniques and electrochemically etched afterwards. Initially, slot arrays with a depth of up to about 0.7 mm could be fabricated. To overcome the instabilities of the mask (normal photo resist) in highly corrosive electrolyte and to achieve more precise and deeper structures, further development and testing of more stable masks are necessary. This investigation is underway. The second method is the classical copying ECM process (C-ECM), i.e. electrochemical copy of a negative structure (tool) onto the workpiece in an almost wear-free manner. Tests with constant DC show that dissolution and structuring of W are possible, but with a rather poor quality of the true structure compared to the tool geometry. First tests with pulsed DC give indications of process improvement and the potential for development to reach a better structure quality. W parts produced by both ECM methods have smooth surfaces without any surface damage (no microcracks), which is favourable for a reduction of peak stresses. Investigations of the optimisation of W shaping are underway. The PIM process begins with compounding the moulding mass, the so-called feedstock, that consists of about 50 vol.% polymer binder and powder of the material to be processed. To shape the so-called green compacts, the feedstock is injected into a closed tool with a cavity that consists of feeder and runner systems and moulds having the inverse shape of the green compacts. After this thermoplastic shaping process, the green compacts are released from binders and become so-called brown compacts which are then sintered to dense products at about 2500 °C for W. In PIM experiments using tungsten powder with a particle size of about 2 μm, the initial micro-structured demonstration components, such as slot arrays and gear housings, have been replicated. Tensile test samples of W have been replicated both in micro and macro dimensions for the determination of fracture toughness after sintering. Also thermal conductivity of the sintered samples will be measured in order to demonstrate the suitability of the injection-moulded components for divertor applications.

4.3. Technological experiments

Technological experiments have been performed in cooperation with EFREMOV with respect to: (a) joining of the W tile to the W alloy thimble, (b) joining of the W thimble to the steel structure, (c) study of tungsten grades suitable as thimble material, (d) E-beam thermo-cyclic (non-isothermal) testing of mock-ups (without He-loop), (e) definition and manufacturing of W mock-ups for HHF-experiments in a He-loop based on the outcomes of a–d (see detail in [10,11]). For the investigation of W/W joining [10] by means of high-temperature brazing, different brazing alloys were used. The screening tests of mock-ups with W/W flat joints have shown that the joints produced with STEMET 1311® filler metal (Ni-base, 16.0Co, 5.0Fe, 4.0Si, 4.0B, 0.4Cr, Tbr = 1050 °C) are reliable enough

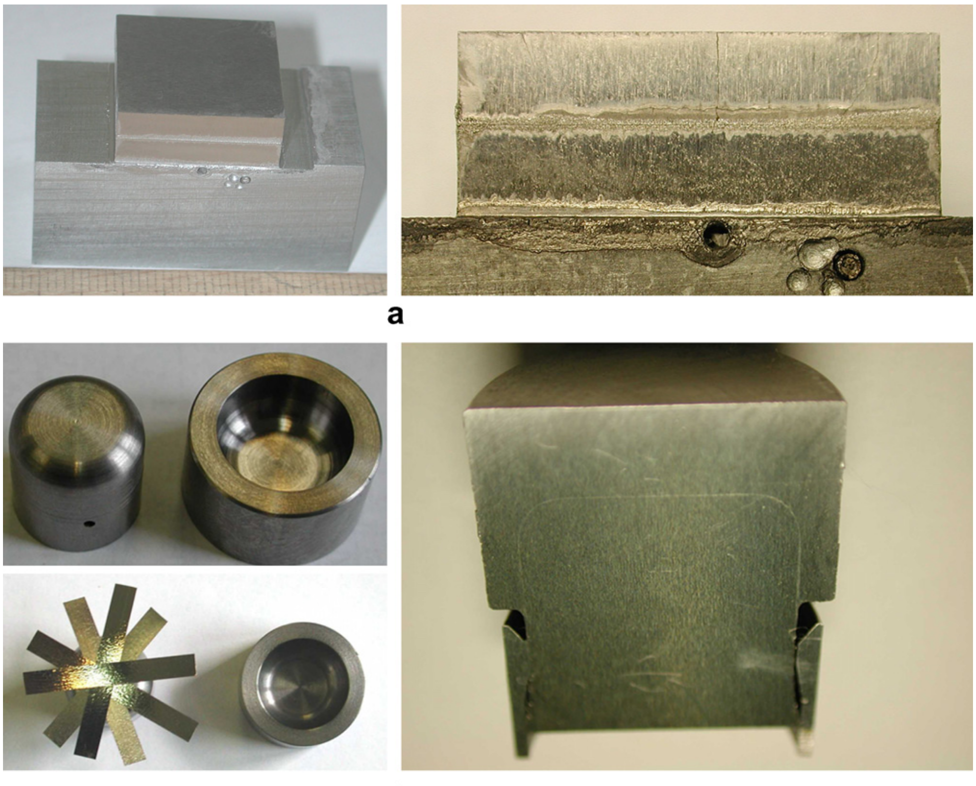

Fig. 3. W/W joint successfully brazed with STEMET 1311®, (a) flat W samples, survived up to 100 temperature cycles at 16 MW/m^2, (b) real cured geometry, survived up to 100 temperature cycles at 14 MW/m^2.

at temperatures in the joint of about 1200 °C and up to a heat flux of 15 MW/m^2. Brazing of the real geometry (in accordance with the design) of a curved tile–thimble interface was performed using the same filler metal in the form of strips of 5 mm width and 40 μm thickness. The strip was cut into pieces of about 30 mm length and placed into the gap between the joined parts in the form of a star. The brazing gap between the joined parts was about 40 μm. Spacers were not used. Some pressure was applied during brazing by means of a jig. The brazed joint was HHF-tested using the method applied to W/W joints (with water-cooled heat sink). It was shown that a brazed W/W joint with STEMET 1311® is reliable enough up to a heat flux of 14 MW/m^2 for a realistic geometry of a helium-cooled divertor (Fig. 3). Long-term testing, including monitoring of the mechanical properties, microstructure, and phases in the brazing zone, will be subject of future tests and may give hints for the improvement of the filler alloys used. For W/steel joining [11], several options, such as screwing, bayonet joining, and a conic lock design with copper casting have been investigated. The latter is preferred. A mock-up with a conic lock and WL10 thimble successfully survived 10 thermocycles (600 °C-RT) at an internal pressure of 10 MPa.

4.4. Thermohydraulic experiments

First thermohydraulics screening tests of various HEMJ and HEMS design variants were carried out at the Efremov's gas puffing facility (GPF) [12]. The experiments were based on a reversed heat flux method, i.e. hot helium (inlet/outlet temp. of 700 °C/600 °C) was pumped through the built-in CuCrZr and/or brass divertor mock-ups to estimate their thermohydraulic efficiency (pressure loss and heat transfer coefficient) when cooled by 100 °C water coolant at the top of thimble. Results of accompanying computational fluid dynamic (CFD) calculations show a good agreement between calculated and measured values of pressure loss, with the exception of one case of a HEMJ mock-up which shows a pessimistically large deviation possibly due to its hole diameter which was found to be increased by approx. 5% due to manufacturing. Also the maximum divertor performance determined by CFD analyses (approx. 12 MW/m^2 for HEMJ and 10 MW/m^2 for HEMS, respectively, for nominal case) agrees well with the experiments.

5. Conclusions and outlook

In this report, the conceptual design and development strategy of a He-cooled divertor have been described. In cooperation with the Efremov Institute, comprehensive technological investigations have been accomplished covering the areas of W/W and W/steel joining, HHF tests, tungsten grades study and mock-up fabrication as well as thermohydraulic screening tests for divertor design variants. From these results, it can be concluded that preliminary candidate materials (WL10 and Eurofer) and technological solutions (STEMET 1311® brazing for the W–W joint and Cu casting with conical lock for W-steel joining) have been found. Several single-finger mock-ups have been manufactured on this basis for the 2005–2006 HHF tests in a helium loop that is presently being built at the Efremov Institute. Further experimental programmes for 9-finger mock-ups are planned for 2006.

Acknowledgements

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