Development of He-cooled Divertors for Fusion Power Plants

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Abstract. Within the framework of the European power plant conceptual study (PPCS), different helium-cooled divertor concepts based on different heat transfer mechanisms are being investigated at ENEA Frascati, Italy, and Forschungszentrum Karlsruhe, Germany. They are based on a modular design which helps reduce thermal stresses. The design goal is to withstand a high heat flux of about 10-15 MW/m^2, a value which is considered relevant to future fusion power plants to be built after ITER. It is an additional challenge that many physical and material-specific factors of the future reactors are unknown. A first design approach and the state of the art of divertor development shall be subject of this report.

1. Introduction

Developing a divertor concept for future fusion power plants to be built after ITER is a challenging task, as it is associated with many factors of uncertainty, such as the physical boundary conditions (e.g. incomplete operation scenario between the high-power operation tokamak physics and the proposed approach) and the properties of the candidate materials envisaged for the divertor concept (see chapters 2-3). Many materials properties are subject to physical limitations, by which the ranges of application of the materials are limited. Existing properties of W-alloy and oxide dispersion-strengthened (ODS) steel are neither well developed nor understood to satisfy all engineering requirements. Many design requirements therefore depend on future achievements and can only be extrapolated from the present stage of knowledge. At this stage, the W-divertor is a potential solution approach, but by no means the perfect one. However, further development is needed to understand the implications of such an approach.

The main function of the divertor is to remove the fusion reaction ash (α-particles), unburned fuel, and eroded particles from the reactor, which adversely affect the quality of the plasma. As one of the high-heat-flux components of the fusion reactor, the divertor has to resist a high surface heat load of up to 15 MW/m^2 depending on the reactor type and physics. In addition, it serves as a shield for the magnetic coils behind it.

Helium coolant is considered a suitable solution for cooling the divertor, as it is compatible both with refractory metals used as divertor material and with any kind of blanket systems, in particular with those blankets that contain beryllium, where water cooling would lead to considerable safety concerns as regards the steam-beryllium reaction with H production. Another advantage of the use of helium coolant is that helium gas allows for a relatively high outlet temperature and, hence, a high thermal efficiency of the power conversion systems.

Retrospect: The development of the He-cooled divertor began within the framework of the EU power plant conceptual study/plant availability (PPA) in 1999 and the power plant conceptual study (PPCS) in 2000. The first He-cooled divertor concepts [1] were based on plate design, such as the unconventional design (1999) with a maximum heat flux of approx. 5 MW/m², the innovative simple slot design (2000) with a heat flux limit of about 6 MW/m², and the modified slot concept (2001) with a heat flux limit of about 10 MW/m². Since 2002, modular divertors have been designed, which help reduce the thermal stresses. Two modular divertor concepts are being pursued within the current PPCS [2]: the ENEA concept HETS [3] (High-efficiency thermal shield) and the FZK concept HEMJ [4] (He-cooled divertor with multiple jet cooling) which has been further developed as an alternative to the forerunner design variants HEMP/HEMS [5, 6] (He-cooled modular divertor with integrated pin/slot array).

2. Design requirements and boundary conditions

General divertor design requirements are: a) ability to resist a peak heat load of at least 10 MW/m², b) keeping the operation temperature window of the divertor within the allowable range that is determined by the ductile-brittle transition temperature (DBTT) and the recrystallisation temperature (RCT) of the structural components made of refractory alloys (e.g. tungsten lanthanum oxide) under irradiation, c) to reach a high cooling performance, i.e. keeping as short as possible heat conduction paths from plasma-facing to cooling surface and achieving high heat transfer coefficients (HTC), while keeping the coolant mass flow rate and, thus, the pressure loss as well as the pumping power as low as possible, d) to keep thermal stresses within the design limits (e.g. by means of modular design as suitable solution), and e) joint constructions between the divertor components that fulfill the functions of stopping the crack growth introduced from the plasma-facing side to maintain the integrity of pressure-retaining structural components beneath it and withstanding the thermocyclic loadings for which a realistic number of about 100 has been assumed. For our design development a higher number of about 1000 is envisaged in order to study the fatigue behaviour and recognize the safety margin to assure a high reliability. The coolant is helium gas operated at pressures in the range of 10-14 MPa with an inlet temperature of about 600°C. As a secondary boundary condition, an engineering limit for the pumping power of about 10% related to the thermal power of the divertor should be accounted for in order to achieve a reasonable system efficiency.

Divertor power: In the current PPCS, the dual-coolant (DC) blanket concept (PPCS model C) [7] is used as a basis of divertor design and layout. For easier handling and maintenance, the divertor is divided into cassettes (Fig. 1 left). It is essentially composed of the thermally highly loaded outboard (OB) and inboard (IB) target plates, the dome that contains the opening for removing the particles by vacuum pumps, and the backbone structure or bulk which houses the manifolds for the coolant. The total energy balance of a model C divertor is shown in table 1. The total divertor power amounts to 583 MW. It consists of 335 MW neutron-generated heat power for the divertor bulk (256.2 MW) and target plates (78.8 MW: OB 44.1 MW, IB 34.7 MW) and 248 MW surface heat power (α and heating power) for the divertor target. A power distribution between IB and OB targets of 1:4 was assumed, leading to a surface heat power of 49.6 MW and

198.4 MW for the IB and OB targets, respectively. For a 7.5° divertor cassette, the size of an OB target plate is about 810 mm x 1000 mm (toroidal x poloidal). For the thermohydraulic layout, the boundary condition of moving peak heat flux was also taken into account.

Erosion aspects: The issues of the divertor and first wall lifetime in future tokamaks cannot be completely addressed without considering the consequences of transient events (disruptions and excursion local loading modes (ELMs)) on the in-vessel structures. Indeterminate predictions available for ELM sizes and disruption frequencies do not yet allow conclusions to be drawn on whether the transient events can be facilitated in future tokamaks. Efforts have been made to predict the damage of divertor material surfaces after high heat pulses by means of codes [8] developed at FZK and information [9] obtained from experiments in plasma guns and electron beam facilities. Macroscopically hardly visible small W melt layers of about 80 µm [10] will occur at every transient event. Most of the melt layer (80%) is just shifted sideways and back, forming and strengthening a ripple-like surface roughness of about 0.3 µm. The ripple figures depend on the ELM size. However, the overall effect after many ELMs depends on the degree of chaos of the ELM-to-ELM load distributions, since chaos helps reduce the roughness. For ITER, for example, the erosion rate mainly resulting from the evaporation is predicted to amount of about 0.1-1 cm after 10^5 ELMs, a number that corresponds to about 1000 ITER pulses with a pulse duration of 400 s.

Choice of divertor materials: The high resistance of the armour material against high heat flux (HHF) and sputtering energy required lead to the choice of tungsten as the most promising divertor material [6], because it possesses a high melting point, high thermal conductivity, and relatively low thermal expansion. In addition, it is a low-activating material. Its disadvantages are a high hardness and a high brittleness, which make the fabrication of tungsten components comparatively difficult. Other disadvantages of tungsten are its poor DBTT and RCT values, by which the operation temperature window of the tungsten structure is restricted. This temperature window and the ductility can be increased by adding fine oxide particles (ODS tungsten), with La_2O_3 being regarded the most suitable option for the divertor design. In detail, the W precursors are blended with oxides and subjected to sintering and mechanical processing to achieve high densities. 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 work. Transient events (disruptions and ELMs) have been taken into account, as a 5 mm thick sacrificial layer of the tungsten armour without any structural function is foreseen for an estimated service life of about 1-2 years based on calculations [8] and experiments [9] for ITER. The transmutation rate of W to Re is given in [11] with about 0.2 at% per dpa, leading to approx. 8 at% at 40 dpa expected. Due to the relatively strong decay heat in tungsten, the divertor has to be cooled actively for some weeks after reactor shut-down before removing to the hot cells.

3. Basic design features

The HETS design (ENEA): The HETS concept [3], initially developed for water, has been extended in the past years for use of He as coolant. Studies have been performed to evaluate its suitability in such environment. The concept is based on an abrupt change of momentum of the fluid in order to increase the cooling gas turbulence and, hence, heat transfer. For this purpose, the He flow is impinged on a dome (Fig. 1, centre) at high speed. In detail, flow goes through a

Ø7 mm nozzle, impinges on the heated part of the structure, and then is diverted sideways through a narrow channel of 1.8 mm height at the inlet and 0.9 mm at the exit that is part of a connected manifold. The HETS elements (single “dome” and “mushroom”) are arranged in modules of six (elements in a module are arranged in parallel), and a suitable number of modules can make a divertor plate. These elements are arranged such that both heat transfer and pressure drop (strictly related to the required pumping power) are optimised. The reference values of the He coolant are 10 MPa pressure, an inlet temperature of 600°C (with respect to the DBTT of the proposed materials), and an outlet temperature of 800°C, which corresponds to a temperature rise of 200°C (this value is to be re-evaluated during optimisation). In order to keep the outlet temperature as high as possible, the structure is made of W alloy, which requires joining by brazing. The reference geometric element is hexagonal (1) with a width over flats of 35 mm (20 mm side).

The HEMS and HEMJ designs (FZK): Two design options of the He-cooled modular divertor concept with a slot array (HEMS) and multiple jet cooling (HEMJ) are shown in Figures 2 and 3, respectively. The main design principle common to both options is the use of small tiles made of tungsten (1) as a thermal shield and a sacrificial layer which is brazed to a finger-like (thimble) structure (2) made of the tungsten alloy W-1%La_2O_3 (WL10). The numbers in brackets refer to Figure 2. For safety reasons, the tungsten tiles are designed separately from the thimble to stop crack growth at the joining surface. The cooling finger units containing parts (1) and (2) are fixed to the front plate (transition zone T) of the supporting structure made of the ODS steel (e.g. an advanced ODS EUROFER or a ferrite version of it) by means of e.g. brazing and/or mechanical interlock. The front plate is connected to the back plate by parallel walls, thus forming a stiff structure. All supporting structures and manifold units are made of ODS F/FM steel. The divertor is cooled with high-pressure helium at 10 MPa, which is supplied by an inlet manifold (4). It enters the finger unit at a temperature of about 600°C and flows upwards to cool the plasma-facing wall at the top of the finger thimble. It is heated up to about 700°C before flowing back downwards to the He outlet manifold (5). Both design variants HEMS and HEMJ essentially differ in the heat transfer mechanism. In the first HEMS design, the modules have a nominal width of 16 mm. The W tiles are of quadratic shape with 5 mm thickness, whereas the thimbles are of cylindrical shape with an outer diameter of 14 mm and a wall thickness of 1 mm. A slot array made of tungsten is integrated as heat transfer promoter (3) at the bottom of the thimble by means of brazing to enhance the cooling surface and, hence, increase the heat transfer capacity. The thimble and flow promoter inlay can be manufactured in one piece, if a suitable processing method is available. In this case, the brazing joint between them can be omitted. The alternative concept HEMJ (Fig. 3), however, is based on direct jet-to-wall cooling without flow promoter. This cooling technology offers the advantage of a higher potential performance and easier design with more easily producible parts. The current HEMJ design [4] employs small hexagonal tiles of tungsten with a width over flats of 18 mm. The tiles are brazed to a thimble of WL10 having a size of Ø15 x 1.03 mm. A 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 spacing (i.e. gap clearance between the cartridge and the thimble bottom wall) are decisive parameters that need to be optimised. A conservative layout for a reference load case of 10 MW/m^2 leads to the following nominal geometry: 27 holes (Ø 0.6 mm), jet-to-wall spacing 1.2 mm. In this case, a relatively large hole diameter was chosen at the expense of a reduced cooling capacity to avoid obstruction problems that may possibly be caused by contaminated helium gas.

4. Design-related issues

The development and optimisation of the divertor concepts require an iterative design approach with analyses, studies of materials and fabrication technologies, and the execution of experiments, which sometimes leads to a trade-off between these requirements under economic aspects (e.g. mass production of some components). Predicting the temperatures and stresses by means of computational fluid dynamics (CFD) and finite element (FEM) computer codes is indispensable to ensure that the engineering design limits are not exceeded. In general, the working temperature window of the divertor is limited by the re-crystallisation temperature of the used refractory alloy at the upper limit and by its ductile-brittle transition temperature at the lower limit. Enhancing this temperature window is a challenging task of materials development. Up to now, only some data have been made available for unirradiated refractory metals and even less for irradiated conditions.

Fabrication of divertor parts: Standard fabrication methods (e.g. milling) are not applicable to W and W alloys and to parts with microstructure shapes and relatively high aspect ratios (i.e. the ratio between the height and width of the structure), due to their high hardness and toughness. Several methods of fabricating the promoter (pin and slot arrays) and tungsten alloy thimble unit are being investigated at FZK and Efremov. The promising methods are electric discharge machining (EDM), electrochemical milling (ECM), laser etching (LE), and powder injection moulding (PIM). At Efremov, technological studies and experiments are being performed with respect to e.g. the joining of the W tile to the W alloy thimble and joining of the W thimble to the steel structure (Fig. 2) by means of high-temperature brazing.

Design-accompanying analyses: Independent studies confirmed the predicted performance of HETS in terms of maximum acceptable temperatures and total pressure losses under a heat flux of 10 MW/m^2, which satisfied the requirements. This is due to the high and very effective HTC estimated. The results of simulation calculations for the HETS design [12] show that the maximum temperature for the reference case is within the operating limits of the structural material. The maximum HTC values reached are as high as 60 kW/m^2K. Studies for improving the pressure drop and the structural dome operating temperatures are underway. Experimental studies are planned to further verify the results. For the HEMJ design [4], CFD simulation calculations with the FLUENT code show that the above-mentioned reference HEMJ geometry can withstand 10 MW/m^2 as specified (Fig. 5). For a nominal mass flow rate of a cooling finger of 6.8 g/s, a value that allows keeping the He outlet temperature below the maximum allowable temperature of the steel structure of about 700°C, the maximum temperatures of the tungsten tile and the thimble amount to 1711°C (< ~2500°C allow.) (Fig. 4) and 1164°C (< 1300°C allow.) (Fig. 5), respectively. The mean HTC value amounts to 32 kW/m^2K (Fig. 6). The maximum He jet velocity was calculated to be about 260 m/s and the resulting pressure loss amounts to about 0.135 MPa. The respective pumping power was estimated to be 57 MW for the whole divertor, which corresponds to 9.8% of the total divertor power (Table 1). With the same mass flow rate, the maximum thimble temperature could even be kept below the temperature limit for the W thimble of 1300°C under a heat flux of up to 12 MW/m^2. A smaller mass flow rate of 5.3 g/s would also fulfil this boundary condition at 10 MW/m^2 with lower pressure loss, if the operation temperature window of the steel structure material could be enhanced. Geometries adapted to a higher heat flux of up to 15 MW/m^2 are under investigation. The overall CFD results agree well with the values predicted by correlations. Accompanying stress analyses also show that all stresses are below the permissible (3-Sm) limit.

Technological and thermohydraulic experiments are indispensable to confirm the design and verify the simulation calculations with the CFD codes. In cooperation with EFREMOV, the experiment programs have been defined with the main emphasis on (W/W, W/steel) joining technology and HHF tests of the divertor finger and finger unit by means of a helium loop that is being constructed. The first results [13] show that the best performance of W/W high-temperature brazing could be achieved with the following two filling metal alloys: 71KHCP (Co-base, 5.8Fe, 12.4Ni, 6.7Si, 3.8B, 0.1Mn, P≤0.015, S≤0.015, C≤0.08), brazing temperature (T_{br}) = 1100°C, and STEMET 1311 (Ni-base, 16.0Co, 5.0Fe, 4.0Si, 4.0B, 0.4Cr), T_{br} = 1050°C. In HHF tests in the absence of a He loop, the mock-ups brazed with 71KHCP survived up to 14 MW/m^2 at least. When STEMET 1311 was used for brazing, heat fluxes of up to 16 MW/m^2 at least were survived by the mock-ups. Manufacturing of CuCrZr mock-ups of different designs by means of EDM has been demonstrated successfully. For W/steel joining, several options, such as screwing, bayonet joining, and 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. Prior to the He loop experiments with HHF tests, first thermohydraulics tests by means of a gas puffing facility (GPF) [14] were carried out. These tests 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 divertor mock-ups to estimate their thermohydraulic efficiency (pressure loss and HTC) when cooled by 100°C water coolant at the top of thimble. The layout of the facility and the experiments were accompanied by simulation calculations. Fig. 7 shows first results of pressure loss measurements for the HEMJ design with varying parameters of jet hole diameter D (mm) / jet-to-wall distance h (mm): 0.6/1.2 (J1a), 0.7/0.9 (J1d), and 0.85/0.9 (J1e). The pressure losses calculated by the Fluent code are also plotted in this figure. These calculated pressure losses agree well with the measured values, with the exception of case J1a, which shows a pessimistically large deviation e.g. at the nominal flow rate of 6.8 g/s. This is probably due to an inaccuracy of the drilling. The hole diameter was found to be increased by approx. 5% due to manufacturing. This will be verified later by the He loop experiments which will presumably begin in 2005.

5. Conclusions and outlook

In this paper, several EU designs of a He-cooled divertor concept with different heat transfer mechanisms are described. The designs are based on extrapolations of the materials data and physical boundary conditions from today's knowledge with many factors of uncertainty. Nevertheless, results of systematic investigations of the design variants show that they meet a large variety of requirements, e.g. loading conditions (heat flux limit of 10 MW/m^2, 10 MPa He pressure) and materials and fabrication issues. For the divertor designs, the details of the modular finger units, manifolds, and the cassette body will be further studied, accompanied by CFD and thermomechanical analyses. The development of a suitable W alloy as structural material today is the main feasibility issue. In addition, irradiation-induced properties of these advanced alloys are also needed. Development of the manufacturing technologies for tungsten divertor components will be continued. First evaluation of the pressure loss and determination of the HTC within the limits of accuracy of the GPF experiments confirm the tendency of validity of the design and simulation. Experimental studies are planned to be carried out to further verify the results. A helium loop is presently under construction at EFREMOV for high-heat-flux integral tests of divertor mock-ups and to determine the pressure loss and HTC of the cooling unit for the HEMS, HEMJ, and HETS design variants. It is scheduled to be in operation and to yield first test results in 2005. An electron beam facility is available there, which allows for the simulation of a high heat load of 10 MW/m² at least.

Acknowledgements
This work has been performed within the framework of the Nuclear Fusion Programme of the EU associations and is supported by the European Union within the European Fusion Technology Programme.

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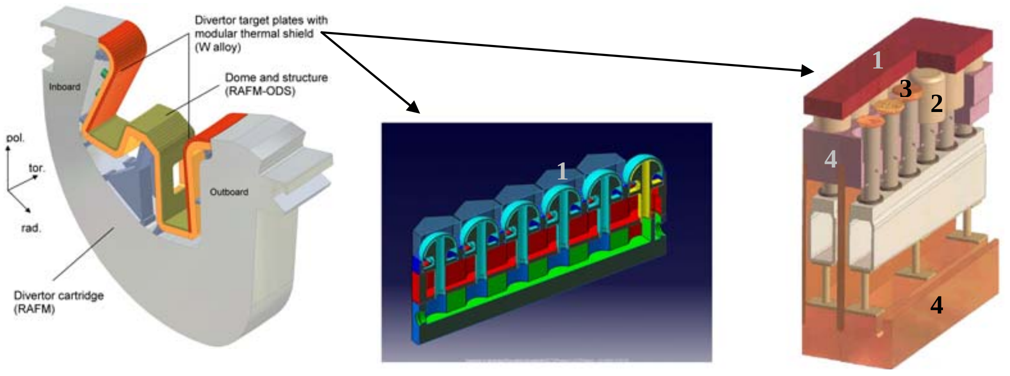
Table 1: Total energy balance of the model C divertor in (MW).

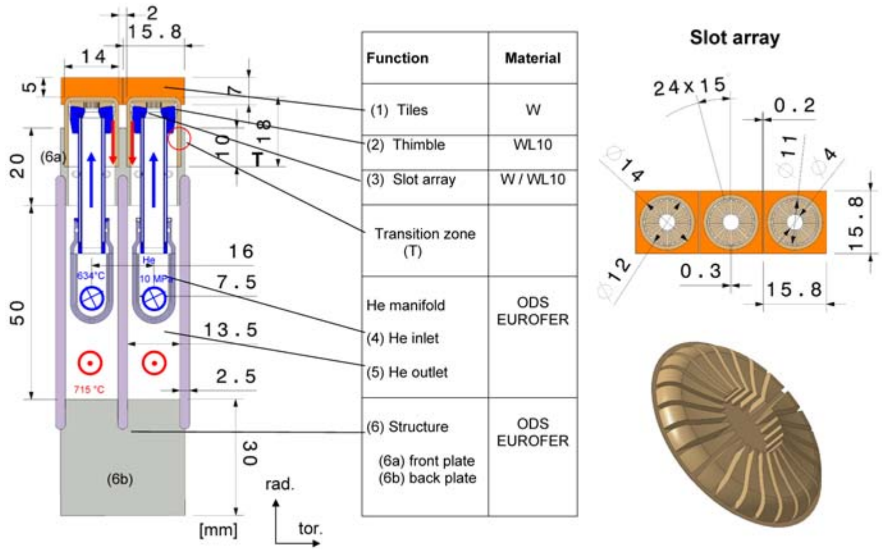
	(A) Surface heat power $Q_\alpha + Q_H$	(B) Neutron heat power Q_n, (56%OB, 44%IB)			(A) + (B) $Q_{48\ cassettes}$	Values for one cassette $Q_{1\ cassette}$
		Targ. pl. *)	Bulk	Sum		
Outboard	198.4	44.1	143.5	187.6	386	8.042
Inboard	49.6	34.7	112.7	147.4	197	4.104
Sum	248	78.8	256.2	335	583	12.146

*) volumetric power density of about 17 W/cm^3



HETS HEMP/HEMS/HEMJ

Fig. 1: Principle conceptual designs of divertor target cooling (1 W armour, 2 W thimble, 3 flow or jet flow promoter, 4 steel structure).



Function	Material
(1) Tiles	W
(2) Thimble	WL10
(3) Slot array	W / WL10
Transition zone (T)	
He manifold (4) He inlet (5) He outlet	ODS EUROFER
(6) Structure (6a) front plate (6b) back plate	ODS EUROFER

Fig. 2: He-cooled modular divertor design with slot array (HEMS).

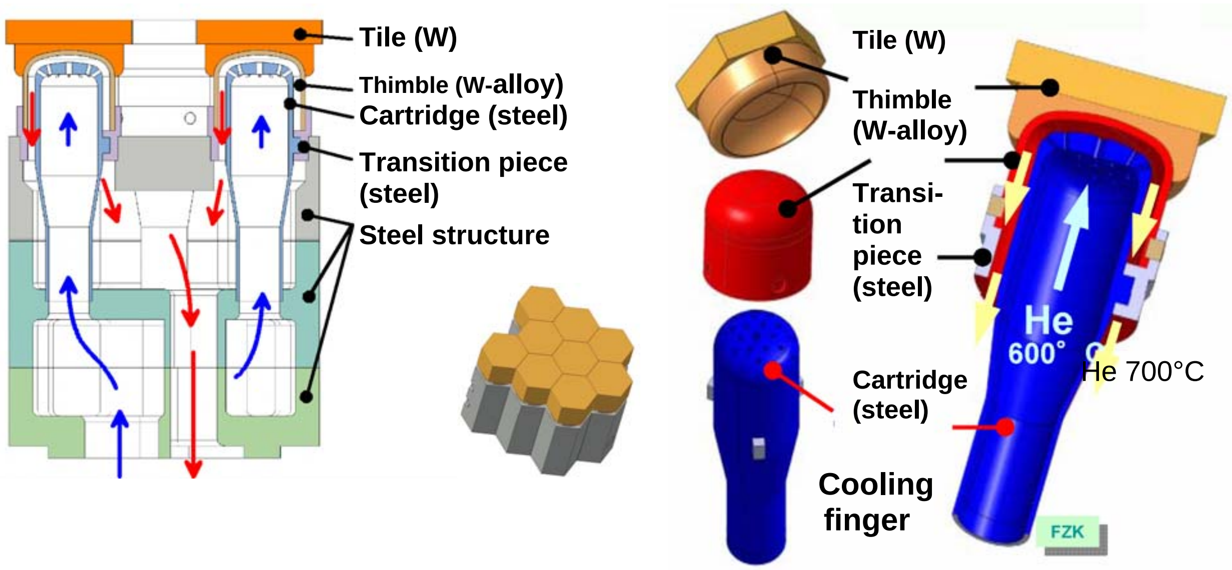


Fig. 3: He-cooled modular divertor with multiple-jet cooling (HEMJ).

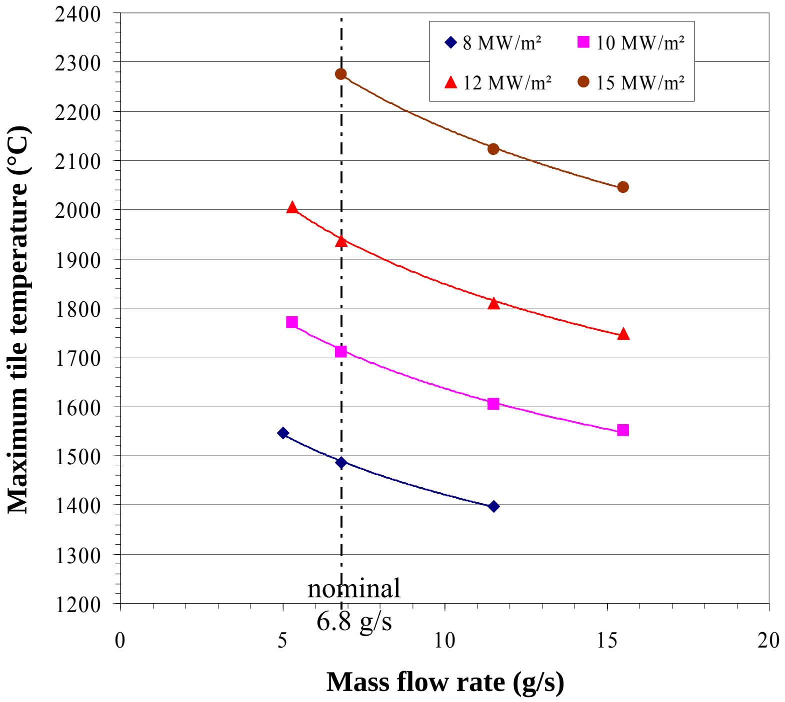


Fig. 4: Maximum tile temperature as a function of the He mass flow rate and heat flux, calculated for the reference HEMJ geometry (J1a).

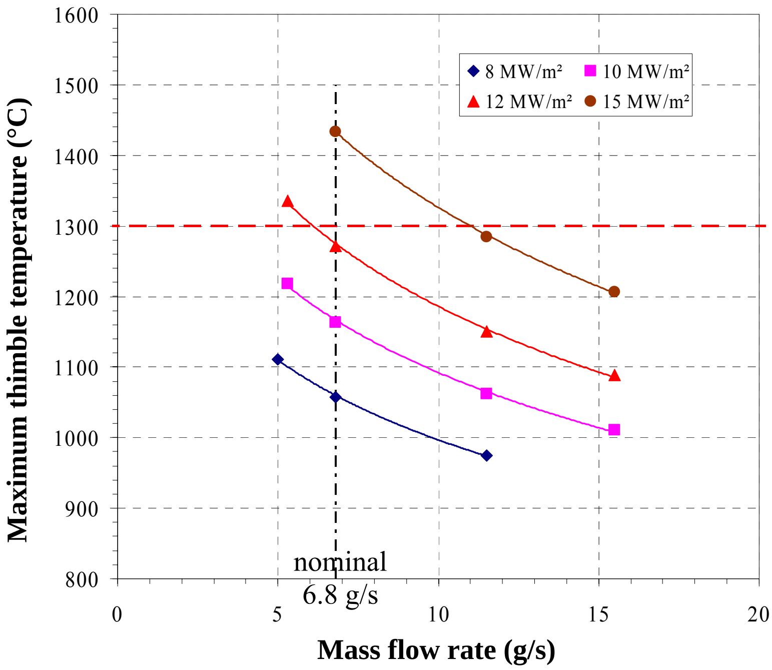


Fig. 5: Maximum thimble temperature as a function of the He mass flow rate and heat flux, calculated for the reference HEMJ geometry (J1a).

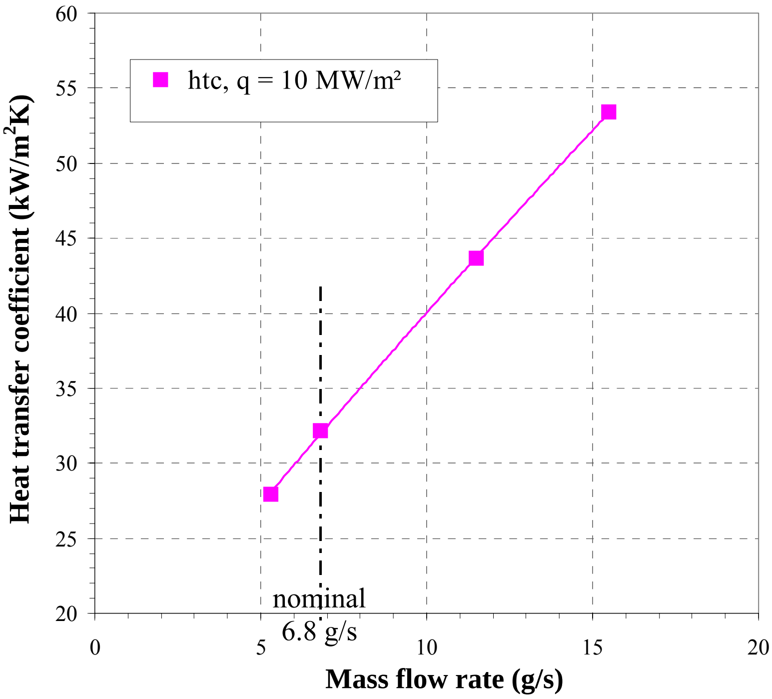


Fig. 6: Mean heat transfer coefficient (related to bulk temperature) as a function of the He mass flow rate, calculated for the reference HEMJ geometry (J1a), q = 10 MW/m^2.

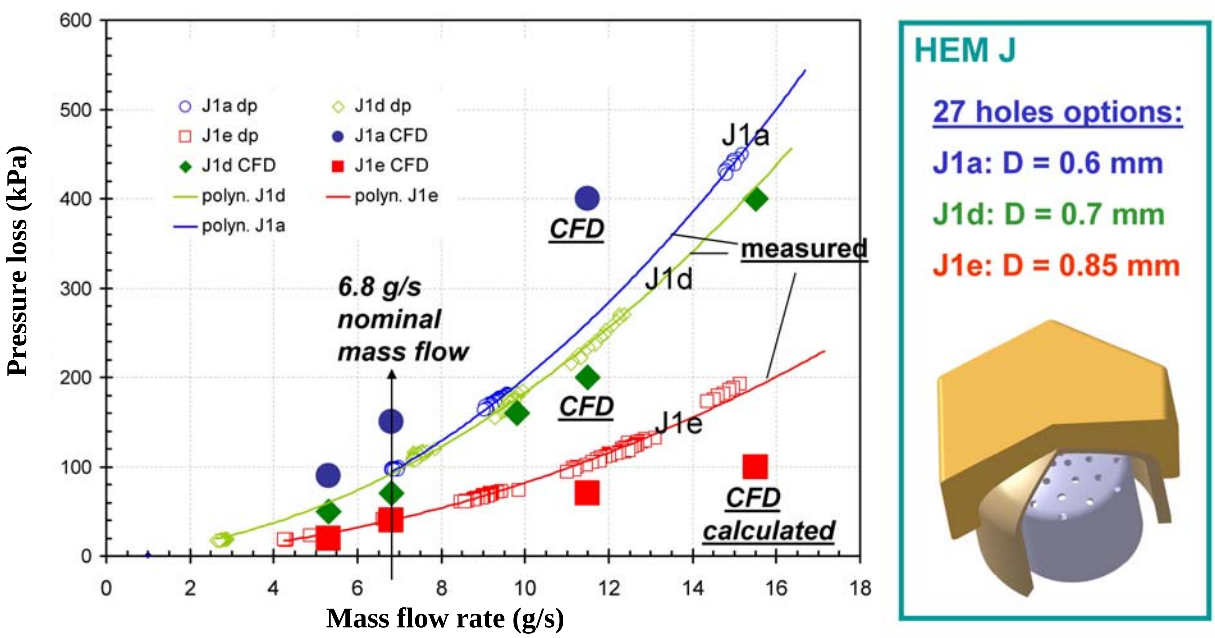


Fig. 7: Measured and calculated pressure losses by CFD code Fluent.