The European Development of He-cooled Divertors for Fusion Power Plants

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Abstract. Helium-cooled divertor concepts are regarded suitable for use in fusion power plants for safety reasons, as they enable the use of a coolant compatible with any blanket concept, since water would not be acceptable e.g. in connection with ceramic breeder blankets using large amounts of beryllium. Moreover, they allow for a high coolant exit temperature for increasing the efficiency of the power conversion system. 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. The development and optimisation of the divertor concepts require a close link of and iterative approach comprising the main issues of design, analyses, materials, fabrication technology, and experiments. Discussion of these issues and of the state of the art of divertor development shall be the subject of this report.

1. Introduction

Helium-cooled divertors are considered a suitable solution for fusion power plants, as they are compatible with likewise He-cooled blanket systems. They are also recommended for those blankets, where water cooling of in-vessel components would lead to considerable concerns in terms of safety (e.g. steam-beryllium reaction with H production). In addition, it allows for a relatively high gas outlet temperature and, hence, a high thermal efficiency of the power conversion systems. 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.

Developing a divertor concept for future fusion power plants to be built after ITER is associated with many factors of uncertainty, such as the physical boundary conditions and the properties of the candidate materials envisaged for the divertor concept. Many materials properties are subject to physical limitations, by which the ranges of application of the materials are limited. Many design requirements therefore depend on future achievements and can only be extrapolated from the present stage of knowledge. The development and optimisation of the divertor concept require a close link of and an iterative approach comprising the main issues of design, analyses, materials, fabrication technology, and experiments.

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 were based on plate design, such as the unconventional design (1999) with a maximum heat flux achieved 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. Later on, modular divertor designs have been adopted since 2002, which help reduce the thermal stresses. Two modular divertor concepts are being pursued within the current PPCS [1]: the ENEA concept HETS [2] (High-efficiency Thermal Shield) and the FZK concept HEMJ [3] (He-cooled divertor with multiple jet cooling) which has been further developed as an alternative to the forerunner design variants HEMP/HEMS [4, 5] (He-cooled modular divertor with integrated pin/slot array).

2. General design requirements and global boundary conditions

General divertor design requirements are: a) Ability to resist a peak heat load of at least 10 MW/m², b) reduction of thermal stresses by modular design, c) keeping the operation temperature window of the divertor whitin the allowable range restricted 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, d) 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, 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 (about 100 – 1000 thermal cycles between operating and room temperatures).

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.

3. Basic design features

In the current PPCS, the dual-coolant (DC) blanket concept (PPCS model C) [6] 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.

The HETS design (ENEA): The HETS concept [2], 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 center) 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 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 oxide dispersion-strengthened (ODS) steel (e.g. an advanced ODS EUROFER or a ferrit 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 [3] 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) being 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 0.6 mm. In this case, a relatively large hole diameter was chosen at the expense of a reduced cooling capacity to avoid obstruction problems possibly caused by contaminated helium gas.

4. Design-related issues

The development and optimisation of the divertor concepts require a close link of and iterative approach comprising the design, analyses, materials, fabrication technology, and 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 CFD and 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.

Choice of materials for the divertor components: 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 [5], 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), such as ThO_2, La_2O_3 or Y_2O_3. 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 referred to as the "design window" range in the following sections. A 2-3 mm thick sacrificial layer of the tungsten armour without any structural function is foreseen for an estimated service life of about 1-2 years.

Fabrication of divertor parts: Standard fabrication methods (e.g. milling) are not applicable for W and W alloys, in particular for 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 [7] 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^{2}K. 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 [3], CFD simulation calculations with the FLUENT code show that the above-mentioned reference HEMJ geometry could withstand 10 MW/m^2 as specified (Fig. 4). 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 1675°C (< ~2500°C allow.) and 1152°C (< 1300°C allow.), respectively. The mean HTC value amounts to 32 kW/m^{2}K. The maximum He jet velocity was calculated to be about 300 m/s and the resulting pressure loss amounts to about 0.14 MPa. The respective pumping power was estimated to 57 MW for the whole divertor, which corresponds to 9.8 % related to 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 admissible (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 [8] 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 and bayonet joining are being investigated. The latter is preferred, but the tightness of the joint still remains to be demonstrated. Prior to the He loop experiments with HHF tests, first thermohydraulics tests by means of a gas puffing facility (GPF) [9] 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 its 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. The first GPF results preliminarily show that the reference case of the HEMJ design (Ø0.6 mm holes, 1.2 mm jet-to-wall gap) seems to be optimum. Provisional evaluation of the pressure loss and determination of the HTC within the accuracy of the experiments confirm the tendency of validity of the design and simulation. This is to be confirmed 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. Development of the manufacturing technologies for tungsten divertor components will be continued. Experimental studies are planned to further verify the results. A helium loop is presently is 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/m^2 at least.

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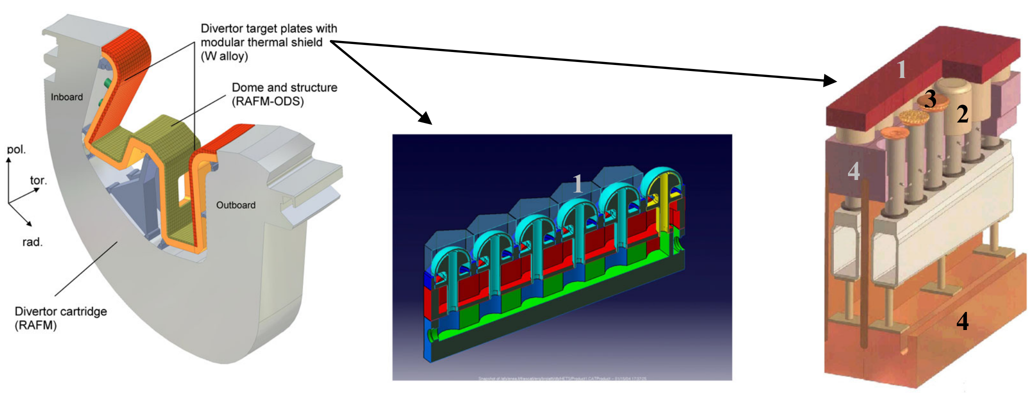


Fig. 1: Principle conceptual designs of divertor target cooling (1 W armour, 2 W thimble, 3 flow or jet flow promoter, 4 steel structure).

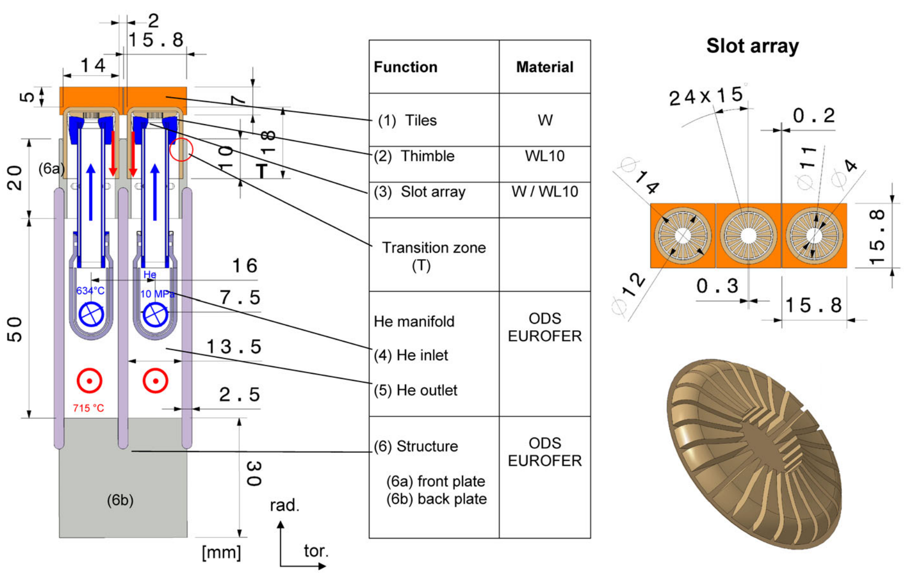
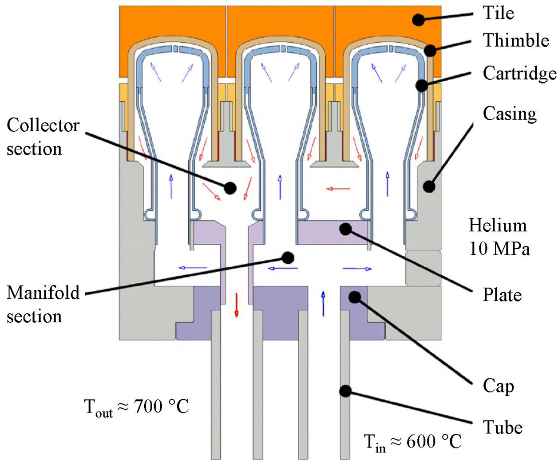


Fig. 2: He-cooled modular divertor design with slot array (HEMS).



cutout of a 9-finger unit

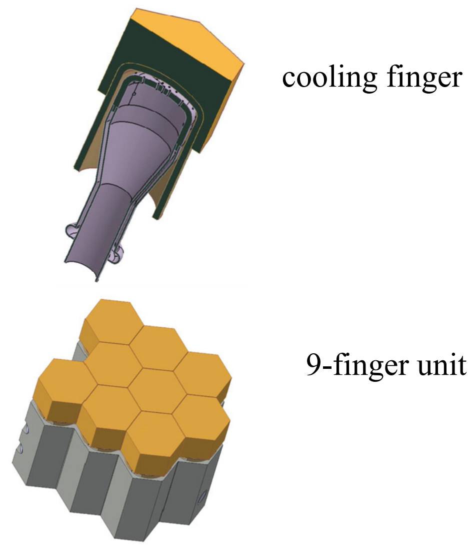


Fig. 3: He-cooled modular divertor with multiple-jet cooling (HEMJ).

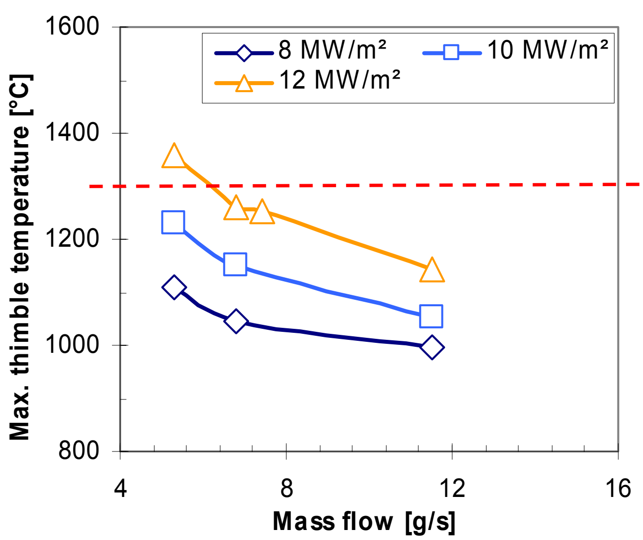


Fig. 4: Maximum thimble temperature as a function of He mass flow rate and heat flux, calculated for the reference HEMJ geometry.

Table 1: Total energy balance of 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 $Q_{1\ cassette}$
		Target plates *)	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