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Multi-design Innovative Cooling Research & Optimization (MICRO): a novel proposal for enhanced heat transfer in DEMO

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Abstract

Several novel design solutions for high performance cooling systems have been developed by Consorzio RFX, permitting to simulate the challenging heat transfer conditions foreseen in the future fusion devices. The project, called Multi-design Innovative Cooling Research & Optimization (MICRO), aims, on one hand, to verify the present solution applied inside the MITICA experiment and, on the other, to perform further improvements in the heat transfer process with an acceptable pressure drop and reliable manufacturing process. A comprehensive parametric investigation has been carried out with the goal of comparing various design options and establishing a standard approach to be applied in several devices, characterized by comparable heat loads both in terms of spatial distribution and amplitude.
The main advantages rely on the possibility to extend the fatigue life-cycle of different high thermal stress components and to investigate the possibility to employ alternative dielectric fluids instead of water. Such design solutions would in fact allow the exploitation of less performing fluids in terms of cooling capability. Despite the unavoidable deterioration of the cooling performances such approach would represent a significantly advantageous option with respect to the existing ultra-pure water technologies. This is particularly relevant in view of DEMO and future power plants characterized by higher efficiency and reliability. The paper gives a detailed description of the Computation Fluid Dynamics (CFD) analysis and the samples manufacturing process.

Keywords: neutral beam injector, cooling technology, high heat flux, computational fluid dynamics, turbulence.

1. Introduction

The Neutral Beam Injectors is a fundamental component for the full-performance exploitation of ITER [1, 2]. The accelerator grids are among the most critical parts of this device, because they must fulfill several operational requirements and at the same time satisfy the fatigue verifications according to the ITER Structural Design Criteria for In-vessel Components (SDC-IC) [3, 4].
In the last five years, a considerable R&D effort has been devoted by Consorzio RFX to the optimization of cooling systems for high heat flux components [5, 6].
In the framework of the EUROfusion Work Package Heating and Current Drive (WPHCD) work program within the Power Plant Physics and Development (PPPT) activities, the MICRO project (Multi-design Innovative Cooling Research & Optimization) aims at a further improvement of high-performance cooling systems, in terms of cooling capability and reduced pressure drop, with a general approach not necessarily limited to the fusion experiments.

2. Design Description

Since the spatial distribution of the heat load is a crucial element for the definition of a high performing cooling system design, the present work focuses in particular on one of the most challenging cases: the beam halo loads. These are characterized by a typical annular distribution along a given grid aperture with peaks of 10 kW/cm^2 and overall 1.4 kW to be evacuated per beamlet, causing an elevate cooling complexity on a boundary edge; the reference load is hence given by the most critical “halo” flux which is supposed to act on the grids [7].

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2.1 Design Constrains

Using a standard design of straight and uniform cooling channels, the fatigue life of the grids was extremely limited below the requirements set by ITER. The main driver for such issue is, in fact, the different thermal expansion throughout the grid, leading to a sharp concentration of stress and strain near the corners of the whole segment [8] It is therefore mandatory to provide solutions for different grid geometries, able to lower the temperature gradients to the maximum reasonable extent without determining an excessive amount of pressure drop along the cooling circuit.
Further structural requirements impose a minimum distance of 1.5 mm between the channel walls and the upstream heated surface, and 1 mm from any other cavity or external boundary. In addition, vibration and erosion issues suggest to put a 15 m/s limit for the water velocity. Finally, a geometrical constrain is imposed by the presence of a 6.4 mm x 4.4 mm cavity hosting the permanent magnets for the suppression of the electrons generated by the stripping reactions [7].
Moreover, since the manufacturing is made by milling, every design should face the technological limit of the minimum diameter of the cutting tool (1.2 mm) set by the manufacturer in order to perform the required penetration depth.

2.2 Present Solution

The NICE (Nozzle Island Cooling Enhancement) acted as the starting point for the development and optimization of further high performance cooling designs

[8]. This solution is able to provide good cooling performance by means of two parallel design guidelines: approaching the channel walls to the heat load footprint (thus reducing thermal conducting resistance) and increasing laminar heat transfer coefficient with the introduction of turbulence due to streamline curvature in the most thermal loaded areas. Furthermore the channel reconnection is another crucial aspect able to guarantee high hydraulic diameter thus limiting pressure losses. The novel design proposals were conceived by further extending these guidelines, considering that, in the heated region, an almost uniform cross section and additional turbulence injection are both wanted.

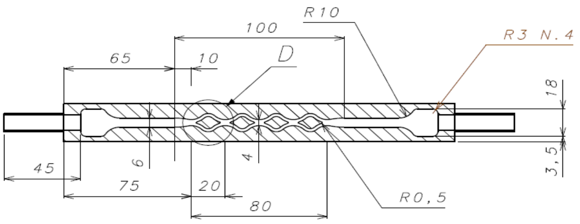

Figure 1 - Technical drawing of present cooling solution

2.3 Research Methodology Approach

Due to the impossibility of reproducing the experimental conditions foreseen in the neutral beam injector, the research activity has been subdivided in three different and consequential steps:

a) Numerical simulations considering the operating scenarios foreseen during the ITER NBI operations [7];

b) Prototype Manufacturing;

c) Numerical simulations considering the operating scenarios foreseen in the ICE facility. This is a facility of Consorzio RFX used to simulate the operating conditions of the cooling systems for high heat flux components [6];

d) Experimental tests in the ICE facility;

The first step provided a numerical test bed for the validity of the new design proposals under the application of the reference thermal loads. The geometries defined in this step provide the manufacturing design input (see Par.4). The third step is instead aimed to benchmark the different fluid-dynamics models in CFX, COMSOL and FLUENT solvers determining how closely the models can predict and match the numerical results with those derived from the experimental campaign in the ICE facility, the final step. Due to the objective difficulties in reproducing the reference thermal load given by the NBI beamlet optic, in this facility the applied heat flux is the one given by the exploitation of ceramic heaters. As a result the spatial distribution of the thermal load is no more annular but uniform (1.16 MW/m^2) along the whole heated surface.

2.4. Novel Enhanced Proposals

After an extensive CAE campaign, ten innovative design solutions, shown in Figure 2, have been considered of technical interest and worth to be manufactured as prototypes. Among the different proposals a single straight channel design (option A) was commissioned in order to test the original solution and the correspondence of its performance with the analytical correlations derived from the literature. The remaining nine prototypes can be categorized according the approach followed to enhance heat transfer. In the former class, the cooling channels are characterized by an increased streamline curvature in order to further enhance the coupling with the thermal loads (see options B2, B3, B4, B5, C1, C2). The first three options B3, B4, B5 are all designed with a wall curvature of 9 mm, blended in a way to leave 2.5 mm from the upper and lower edges. The different sub-channels are all characterized in the different geometries by the same minimum available width (1.2 mm), able to guarantee the highest ratio between *wet surface* and *transversal cross section.* The main difference between the three different solutions is in the design of the elements routing the flow in the different sub channels (e.g. minimum copper space between channel walls, common fluid mixing central zone, and separated sub-flows).

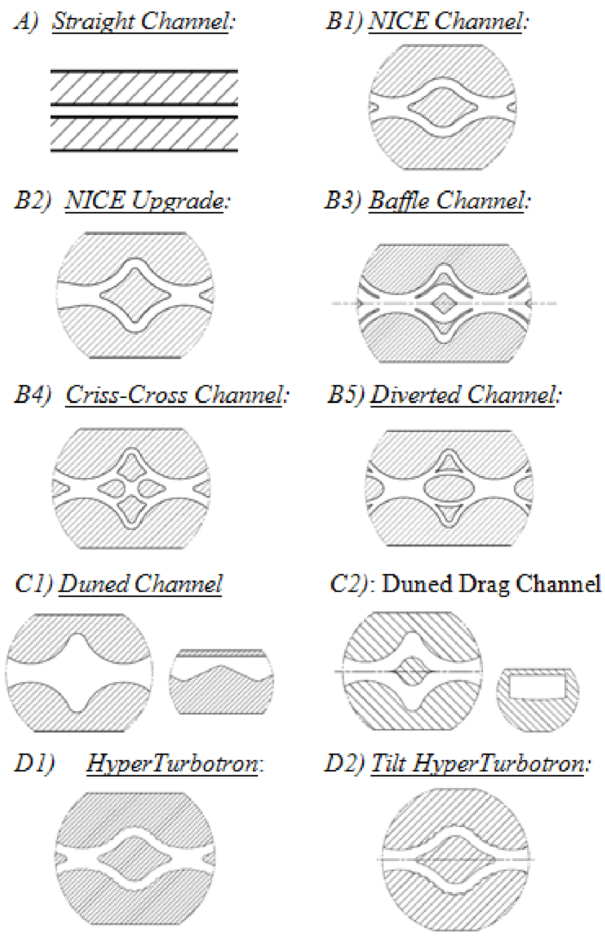

Figure 2 - Schematic representation of SCP designs

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Options C1 and C2 propose instead of the previous techniques, a compensation of the increasing channel height by lowering its depth. The particular heat load topology has further suggested the interposition of a central body in the *Duned Drag Channel* in order to increase the wet surface and re-routing the flow in areas characterized by higher heat loads. A drawback is the necessary reduction of the lower wall slope in order to limit hydraulic losses. Option B2 is similar to the standard NICE solution (option B1) but the island separating the two branches is larger and the upper/lower curves sharper. The latter class of proposal is, in terms of design, the exact reference solution (option B1) but with the introduction of additional turbulence injector devices. Such injector devices consist of 11 blended ribs tilted with respect of the streamline direction by an angle of 90° (i.e. perpendicular) or 45°. These ribs are designed with a radius of 0.25 mm, along a wall curvature of 9.25 mm so that the minimum distance from the aperture is kept the 1 mm, as from constrains. The depth of the ribs is 2 mm, as this value was numerically found to be the asymptotic limit for increasing heat transfer coefficient without severe penalization in terms of pressure drops. All the different proposals have been assessed with sensitivity analysis, evaluated in steady state CFD simulations and compared in terms of thermo-hydraulic characteristics. Among these, particular attention was given to pressure drop, laminar velocity and cooling performances. For the sake of brevity here are reported the results obtained implementing the SST as fluid-dynamic model in CFX and Fluent solvers.

Table 1 –Numerical Estimations of Pressure Drop

	CFX		Fluent	
[bar]	**Mitica**	**ICE**	**Mitica**	**ICE**
Baffle channel	1.83	1.76	1.84	1.72
Criss-Cross channel	1.76	1.67	1.74	1.68
Diverted channel	1.79	1.68	1.81	1.74
Duned Channel	1.56	1.49	1.54	1.43
Duned Drag channel	1.78	1.70	1.79	1.67
NICE channel	1.29	1.22	1.26	1.17
NICE Upgrade	1.73	1.63	1.71	1.65
NICE Turbotron	1.72	1.64	1.78	1.71
NICE Tilt Turbotron	1.70	1.59	1.67	1.57
Single Straight	0.92	0.85	0.90	0.82

Table 2 – Numerical Estimations of Maximum Temperature

	CFX		Fluent	
[°C]	**Mitica**	**ICE**	**Mitica**	**ICE**
Baffle channel	220.86	61.75	219.43	60.58
Criss-Cross channel	230.02	67.32	231.85	66.35
Diverted channel	223.54	62.95	222.53	62.89
Duned Channel	231.96	68.59	232.45	68.40
Duned Drag channel	226.44	64.89	224.95	65.84
NICE channel	243.48	73.83	244.23	74.42
NICE Upgrade	232.46	68.78	230.92	67.22
NICE Turbotron	234.91	69.48	235.47	70.57
NICE Tilt Turbotron	233.64	68.83	235.48	68.74
Single Straight	278.31	84.58	280.84	85.74

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Table 3 – Numerical Estimations of Channel Wall Velocity

	CFX		Fluent	
[m/s]	**Mitica**	**ICE**	**Mitica**	**ICE**
Baffle channel	16.78	16.43	17.54	17.23
Criss-Cross channel	15.13	15.24	16.84	14.83
Diverted channel	15.51	15.82	16.47	15.24
Duned Channel	14.04	13.57	14.87	13.21
Duned Drag channel	13.66	12.95	13.73	12.52
NICE channel	12.60	12.57	12.74	11.89
NICE Upgrade	20.04	19.47	21.47	20.73
NICE Turbotron	15.52	14.86	15.92	14.62
NICE Tilt Turbotron	14.67	14.42	15.01	14.27
Single Straight	9.29	9.14	9.64	9.02

3. Manufacturing

Due to the close collaboration with internal and external technicians during the design phase, the manufacturing process did not show particular criticalities. All the different geometries, with the exception of the Tilt HyperTurbotron, have been realized with high accuracy by the machinery owned by the external company demonstrating the technological reliability of the manufacturing process. As far as the difficulty in the realization of the inclined ribs is concerned, that is due to the employment of a 3-shafts milling rather than a 5-shafts one. Although the ribs were projected with a fixed tilt of 45° along the streamline direction and no inclination in the transversal plane, the different channel wall curvature encountered by the mill while penetrating the material did not allow the tool to accomplish the design realized on the CAD. The ribs were eventually realized just in those regions where the curvature did not turn from concave to convex along the milling direction. In all the others the bad curvature trend did not permit to the mechanical tool to be held in position by a sufficient material thickness.

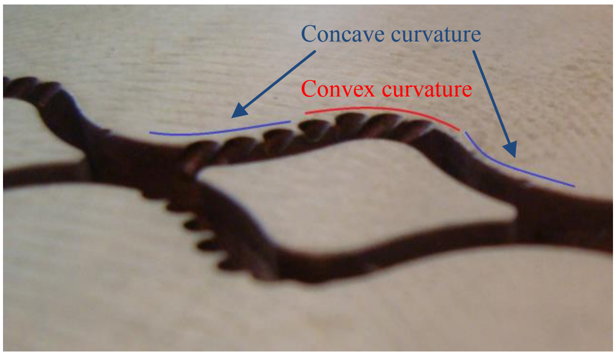

Figure 6 – Detailed view of the inclined ribs

In the event that such geometry would reveal so performing to be worth of further manufacturing, present shortcoming can be avoided either by employing a 5-shafts tool machine or prototyping with a higher accuracy the position where the mill would start the realization of the ribs. The other two possible criticalities individuated during the design phase were the minimum copper thickness (0.8 mm) inside the Baffle Channel

Design and the realization of the narrowest sections inside water channels (1.2 mm) with standard milling equipment which would not be damaged due to the vibrations and mechanical stress. Both issues were successfully accomplished and in case the most performing geometries would be the ones characterized by such characteristics, it could be taken into consideration to prototype the next generation of designs with a more challenging specification (0.7 mm for the copper gap and 1 mm as the minimum water channel cross section). Before starting the electro-deposition process the slab has been characterized in terms of channel wall roughness. The measurements defined an average roughness of 1.3 μm along the frame regions and 1.6 μm inside different heat transfer groups. Such information will be employed in the numerical simulations in order to individuate, if exists, a superficial sand grain dimension optimum for the minimization of pressure drops. The external company was eventually asked to provide the global manufacturing time for each prototype in order to get a preliminary comparison in term of costs for the different designs. Such approach is particularly coherent when, like in this case, the final price is mainly due to the time employed by the machinery to realize the geometry.

Figure 7 – Overall view of the manufactured copper slab

The overall index of cost is then obtained as a relative ratio between the manufacturing time for a given design and the one needed for the realization of present reference solution (NICE channel).

Table 4 - SCP manufacturing time and relative index of cost

Geometry	Manufacturing Time	Cost Index
Baffle channel	4 h 00 min	4
Criss-Cross channel	4 h 40 min	4.67
Diverted channel	4 h 45 min	4.75
Duned Channel	1 h 00 min	1
Duned Drag channel	1 h 30 min	1.5
NICE channel	1 h 00 min	1
NICE Upgrade	1 h 00 min	1
NICE Turbotron	2 h 30 min	2.34
NICE Tilt Turbotron	3 h 15 min	3.25
Single Straight	50 min	0.83

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Conclusions and Perspective

In the framework of the MICRO project, a set of novel proposals for advanced cooling channels for high heat flux components have been developed by Consorzio RFX. By means of detailed CFD simulations, a part of them have been found to improve the cooling performance when subjected to high heat fluxes. Based on these information, the most promising design option have been used to manufacture a new set of Single Channel Prototypes, that will be tested in a dedicated facility in the next future. The tests will be executed both with ultra-pure water and dielectric fluids verifying the cooling performance and possible erosion or vibration issue. Once the thermofluid-dynamics characteristic of the different SCPs have found a coherent CAE modeling, the same geometries will be numerically tested on a full size segment of accelerating grid in order to have a complete CFD and structural characterization.

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