IT9500094

A High Performance Water-Cooled Thermal Shield Device

A. Pizzuto, C. Sangiovanni
Associazione EURATOM-ENEA sulla Fusione, Centro Ricerche Energia Frascati,
C.P. 65 - 00044 Frascati, Rome (Italy)

ABSTRACT

The shielding of the heat flux coming from plasma is one of the most limiting factors in plasma-facing component (PFC) design. In fact, the performance of a cooled divertor plate system is mainly limited by the heat transfer capability (maximum value of the critical heat flux CHF) and by the capability to sustain thermal stresses, even if the maximum allowable heat flux is determined by the thermal conductivity of the protective material (maximum temperature value on the plasma facing surface). A new concept for cooled thermal shield design was devised and tested. Analyses and tests demonstrate that the new concept introduces very high improvement in PFC design, in terms of both heat removal capability (very high CHF) and related stress performance. Up to 80 MW/m² under steady state were successfully applied.

INTRODUCTION

One of the most critical problems that limit the performance of the machine for magnetically confined nuclear fusion research consists in shielding increasingly higher heat loads coming from plasma.

In fact, in this field, critical heat fluxes one order of magnitude greater than those required in fission plants are necessary.

Obviously, the most ambitious design challenge is to have a shielding device capable of withstanding heat loads up to several tens of MW/m².

The aim of both the design and the experimental work was to face such a difficult problem.

The approach followed is very innovative: a shielding device capable of a better thermohydraulic performance than required by the next-step machines was devised and successfully tested.

I. THERMAL SHIELD CONCEPT

Basically, this concept provides heat removal by utilizing the vaporization latent heat of a fluid (as is fairly normal) with the addition, however, of an innovative and very effective method of boundary layer regeneration. Thus, the nucleate boiling process can be maintained with high reliability.

Manuscript received October 14, 1993

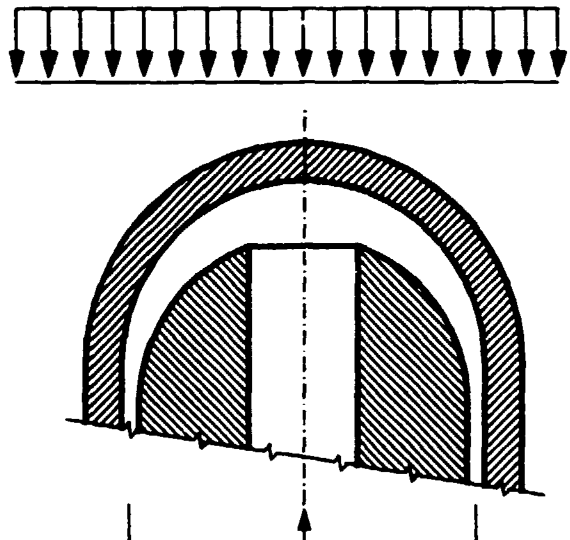


Fig. 1 Concept schematic

The method consists in utilizing a fluid flow characterized by a strong velocity component perpendicular to the heated wall.

The velocity component is obtained by means of a rapid and sudden variation of the fluid current direction, which originates a high centripetal acceleration, until it is reversed (Fig. 1). The apparent fluid density may reach values several orders of magnitude greater than the real value.

II. THERMAL SHIELD GEOMETRY

The shield has a modular structure. It consists of an array of elementary components (Fig. 2) assembled so as to obtain the required shape. Depending on the thermohydraulic parameters to be achieved, they can be hydraulically connected both in series and in parallel. In any case, very good geometric versatility is assured. A very important feature of the concept is the capability to lower the relevant thermal stresses. This enhances the performance achievable by the concept, which is based on a tubular structure (limited above

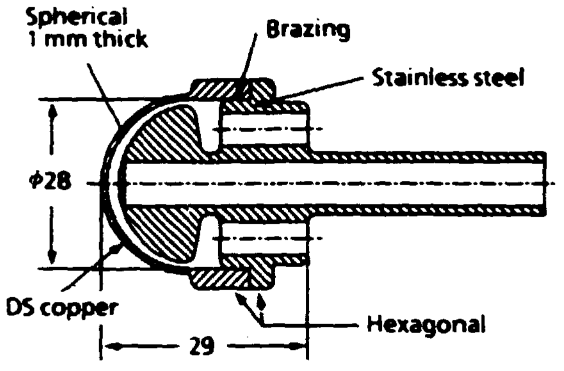


Fig. 2 Elementary component (Mushroom)

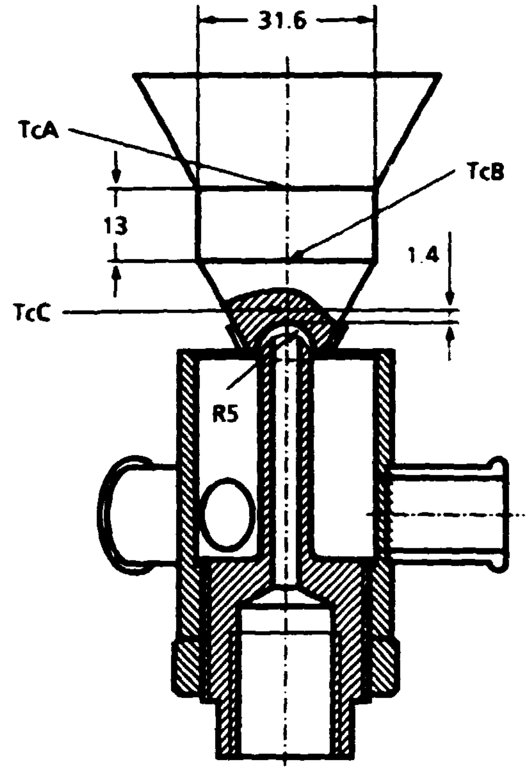


Fig. 3 Test mockup

all by the bending due to the nonuniform heat load), even from the thermomechanical point of view. Several geometries can be envisaged. One of the most promising is shown schematically in Fig. 2. It consists of a thin as possible hemispherical shell, impinged on its outer side by the heat flux; on the inner side it is faced by a suitably shaped nozzle to obtain the effective cooling channel. This channel is fairly narrow and nonconstant in width.

III. THERMOHYDRAULIC TESTS

A. *Test Description*

To have a preliminary assessment of the shield capability, thermohydraulic tests were carried out on a scaled module having a hemispherical radius of 5 mm (see Fig. 3). The hemisphere is formed of an OF copper massive piece, shaped in order to amplify the impinging heat flux, which is applied on the top surface using a 50-kW oxipropane torch. The gap thickness varies from 1 to 0.5 mm (from the center to the periphery). The water velocity was in the range of $10 \div 15$ m/s. The inlet pressure value was 0.27 MPa, which is also the total pressure drop.

The test bed schematic is shown in Fig. 4. Three thermocouples were applied on the specimen axis: two for heat flux measurements, and one to have temperature values very near to those of the cooled surface. The inlet and outlet water temperatures were monitored by two thermometers.

Tests were made by increasing gradually the heat load up to the maximum limit, which was due to the facility characteristics and not to the cooling capability of the system.

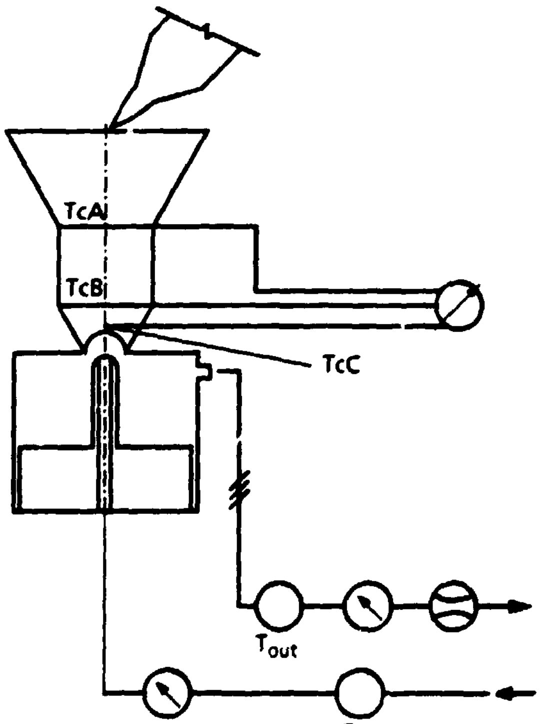


Fig. 4 Test bed schematic

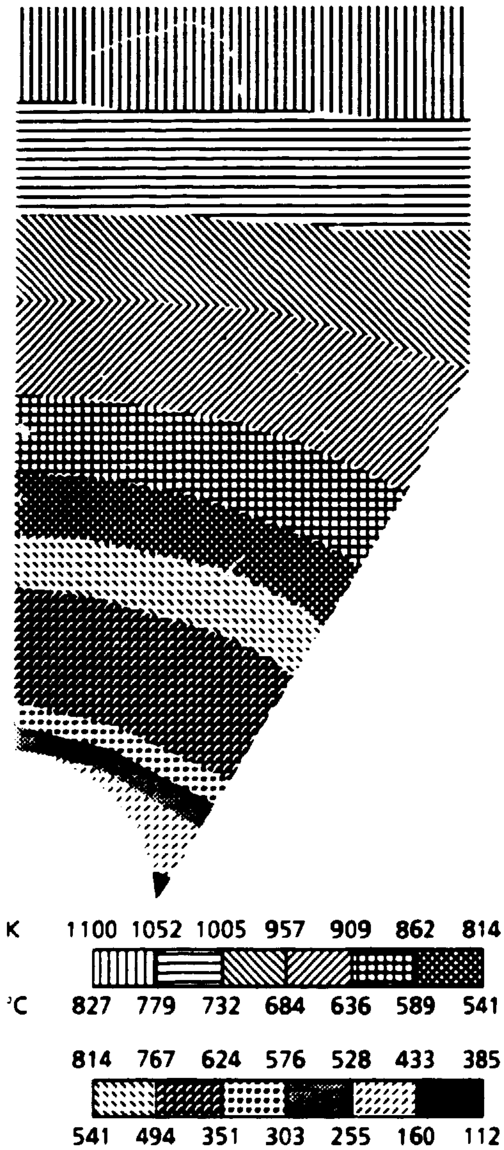


Fig. 5 Temperature distribution

B. Results

The characteristic thermohydraulic values obtained, corresponding to the maximum input power, are the following (referring to Fig. 4):

TcA	827 °C
TcB	630 °C
TcC	362 °C
Tin	19.1 °C
Tout	23.2 °C
Flow rate	0.21 kg/s

The thermocouple and thermometer measurements (which in good agreement) showed that the heat power removed by the water flow is 3.6 kW, which corresponds to a heat flux, through the projected hemisphere surface, of 46 MW/m².

Finite-element (FE) computations were performed to fit the measured temperatures and to evaluate the surface temperatures. Only the most representative portion of the specimen was modelled (Fig. 5). Finite-element models with either temperature or flux boundary conditions were adopted. Both computations reproduce very well the measured temperatures. Preliminary evaluations of the surface temperatures indicate that the mean heat transfer coefficient (HTC) on the hemisphere surface is at least 130 kW/m² K; consequently, the HTC on the projected surface is 260 kW/m² K. In fact, these values are related to a computed total heat power of 3.4 kW, instead of that measured: 3.6 kW.

Tests were repeated on a scaled mushroom, made of dispersion strengthened copper, having a 1-mm-thick shell, 19 mm in diameter. The heat source was a T.I.G torch. Due to geometry limitations, the shell did not carry any instrumentation. The heat flux was focused in a narrow area, where fluxes of at least 80 MW/m² were achieved and maintained for half an hour: no damage was found on the mushroom shell.

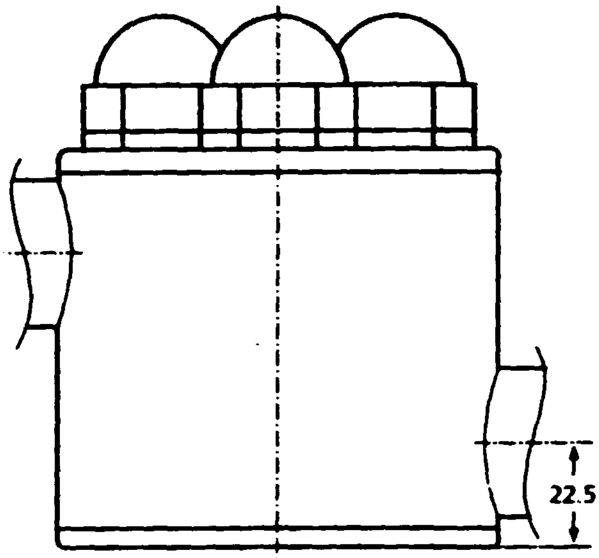
IV. FUTURE R&D PROGRAM

An R&D program aimed at investigating the thermohydraulic and stress limits of the device is on schedule.

The program consists in testing a relevant mockup (Fig. 6), already built, carrying protective tiles or coatings. A source power of about 100kW is needed to test ϕ50-mm modules. A preliminary step can be made, utilizing an existing ϕ20 DS copper module, without any external protection, with a 13-kW source. In both cases the aim is to have a heat flux of at least 50 MW/m² transferred to the cooling water.

V. MOST RELEVANT IMPROVEMENTS ACHIEVABLE WITH THE PROPOSED NEW CONCEPT

The new concept represents a very interesting improvement in PFC design. In fact, the PFC solutions, envisaged up to now, have CHF values very close to the design values. Furthermore, thermal stress values and related displacements are rather high, resulting in a geometric deformation (due to tube bending), which can modify the heat load distribution during operation. From the manufacturing point of view, the solutions consist



of a very large number of tubes. This implies difficulties in alignment, supports, quality assurance and remote handling. Remote maintenance is not feasible. The new concept enhances in a very impressive way the performance of the divertor plate system and introduces very important improvements in manufacturing and remote handling possibilities. With respect to the present solution:

- It has a CHF one order of magnitude greater than that achieved so far; from preliminary tests it can be evaluated as $\geqslant$ 100 MW/m^2.
- It has double the capability to withstand thermal stresses, remaining, practically, globally undeformed. In fact, the stress effect is localized and does not affect the structure as a whole.
- It requires a minor pressure drop and flow rate for each MW/m^2 removed.
- It allows the possibility to modulate pressure drop and flow rate, depending on the region to be shielded.
- It results in a self-supporting structure; hence, remote handling is less critical.
- It has a more effective quality assurance because its geometry is more favorable.
- It can allow in situ tile repair. In fact, it consists of an array of *isolated* cups that can be heated independently, by induction, to allow tile substitution;
- It maximizes the shielding surface, in the case of a radiation-loaded divertor.

A last very important point can be outlined: the considerable amount of power absorbed by divertor plates. The new solution, having a very high heat transfer coefficient, allows a less sub-cooled water, enhancing its thermohydraulic conditions enough for its utilization.

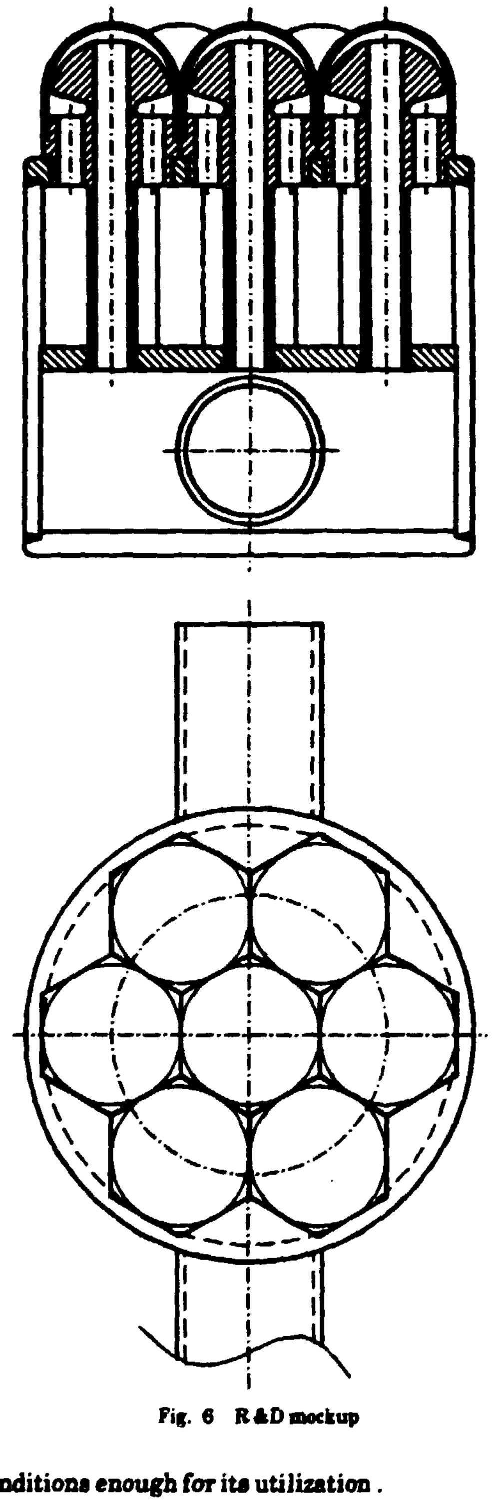


Fig. 6 R&D mockup

ACKNOWLEDGEMENTS

The authors wish to thank Dr. B. Riccardi for performing and analyzing the FE computations.