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Development of ITER Divertor Plate with Annular Swirl Tube and Tungsten Rods

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Abstract

Development of divertor high heat flux components is one of the key issues to realize fusion experimental reactors such as ITER. JAERI has been developing the divertor components to meet the ITER design. In the reference design of the ITER divertor, CFC monoblocks on a swirl cooling tube with pressurized water flow are adapted for the lower part of the vertical target. To increase reliability, an annular flow concept of the CFC monoblocks with concentric feed and return has been proposed and developed. A critical heat flux (CHF) testing has shown the no degradation of CHF of the annular swirl tube in comparison with the conventional swirl tube which indicates its applicability to the ITER divertor cooling. Large-scale vertical target mock-ups have been fabricated and tested in an ion beam test facility. The mock-ups have successfully withstood a heat load of 20 MW/m^2, 15 s for more than 1000 cycles. Thus it is demonstrated that the vertical target with the annular tube can be applicable to the ITER divertor plate.

For upper part of the vertical target, the W/Cu hot pressing method has been also developed to improve the reliability and to reduce the cost. Thermal cycle test was performed on the W/Cu hot pressing divertor mock-up to investigate the durability of the joining interface. As a result, the surface temperature has shown almost constant throughout the experiment, and no degradation of the thermal response was found through 3000 cycles at 5 MW/m^2, which corresponds to the ITER operational conditions for upper part of the divertor.

Keywords:

divertor, ITER, vertical target, monoblock, annular swirl tube, CHF, CFC, CuCrZr

1. Introduction

The divertor plate of ITER will be exposed to high heat loads and high particle fluxes from plasma. The divertor plate for ITER should withstand the heat load of 5-10 MW/m^2 in the steady state operations for several hundreds seconds and up to 20 MW/m^2 in the transient operations for several seconds [1]. To withstand such high heat loads, the divertor plate should be actively cooled. The divertor plate is covered with tungsten in the high particle region because of its low sputtering yield and high melting temperature. It is also covered with carbon based material in high thermal load region because of its high thermal conductivity and high sublimation temperature. In the reference design of the ITER divertor, the upper half of the divertor is covered with the macro-brush tungsten armor and the lower half of the divertor is covered with the monoblock carbon fiber reinforced carbon composite (CFC) armor. These armor tiles are metallurgically bonded onto the cooling tube and the back plate to reduce the thermal resistance. In the cooling tube, a swirl tape is inserted to enhance

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the heat transfer performance.

The divertor plate has many cooling tube to remove such high heat loads. These tubes are required to weld for the water manifold into the limited space of the vertical target [2]. To reduce the welding process and to develop the alternative concept for the vertical target cooling system, an annular flow concept of the CFC monoblock with concentric feed and return is proposed. Figure 1 shows the conceptual design of the vertical target with an annular tube. In this design, cooling water flows inside of the stainless steel inner tube at first, and then returns in an annulus between the outer tube and the inner tube with a swirl fin. To investigate the thermal performance of the annular tube with swirl flow, thermal hydraulics testing was performed.

For the W/Cu joining techniques, JAERI has newly developed the W/Cu hot pressing method to improve the reliability and to reduce the cost. In this method, the W rods were used for armor material instead of the W plate to reduce the joining area. The W rods are inserted into the corresponding holes on the Cu substrate by hot pressing. This W rod was made of the commercially available type W to reduce the cost. To investigate the durability of the joining interface, thermal cycling tests of a small mock-up were performed.

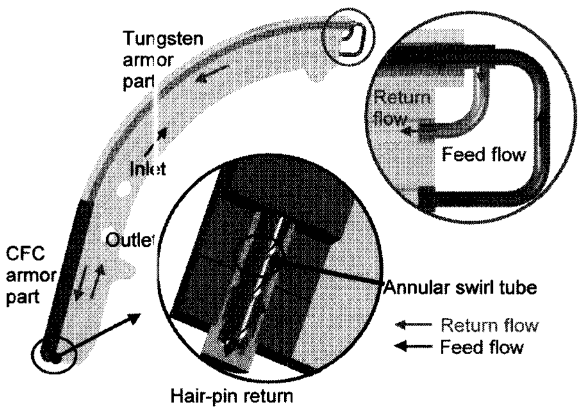

Fig. 1 Schematic of the ITER vertical target with an annular swirl tube

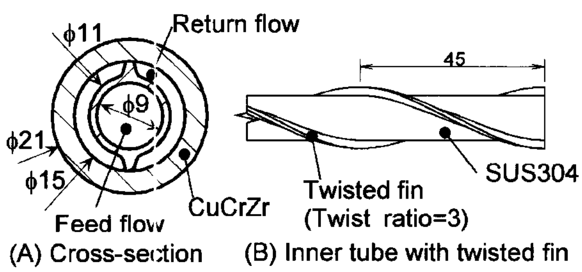

Fig. 2 Detail of the annular swirl tube

2. Development and Heating Tests of Large-Scale Divertor Mock-Up with Annular Swirl Flow

2.1 Critical Heat Flux Testing on the Annular Swirl Flow

Although a lot of critical heat flux (CHF) experiments for the other cooling structures have been reported, a few data have been presented on the annular swirl flow under ITER-relevant conditions [3]. Therefore, CHF testing of the annular swirl tube has been carried out. Figure 2 shows the details of the annular swirl flow mock-up. The annular swirl tube consists of two concentric tubes. The outer tube with outer and inner diameters (OD and ID) of 21 mm and 15 mm is made of CuCrZr. The inner tube is made of stainless steal, and has an external swirl fin with twist ratio of three to enhance its heat transfer performance. The twisted fin is made with direct milling from a thick tube. In this mock-up, the cooling water flows in the inner tube at first and a nozzle feed the water into the annular gap between the outer and inner tubes at an end-plug. Thermocouples are also brazed into the tube wall to detect the transient temperature response for incident critical heat flux.

CHF tests on the annular swirl flow were performed in an ion beam facility of JAERI [4]. Incident heat flux profiles on the surface of the mock-up along the flow direction are almost Gaussian profile with a full-width at half maximum of 150 mm. Cooling conditions were as follows, axial flow velocity at the

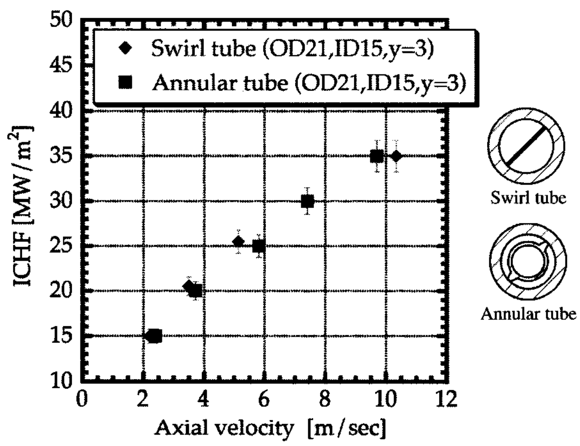

Fig. 3 ICHF for an annular swirl flow in comparison with a swirl tube

annular section ranged up to 14 m/sec. Local pressure was about 1 MPa. The inlet water temperature was room temperature. At the constant heat flux condition, the axial velocity was decreased step by step to occur the burnout or rapid temperature rise detected by the thermocouples in the tube material.

Figure 3 shows the incident critical heat fluxes (ICHF) for the annular swirl flow as a function of the axial flow velocity at the annular section. They are compared with ICHFs for the swirl tube that has the same outer tube geometry of the annular tube as shown in Fig. 3 and same twist ratio of the swirl tape. From these results, there was no degradation of ICHF of the annular swirl tube in comparison with the conventional swirl tube.

2.2 Large-Scale Vertical Target Mock-Up with Annular Swirl Flow

Large-scale vertical target mock-up with annular swirl flow has also been fabricated. Figure 4 shows the photograph of the mock-up. Two-directional (2D) CFC were selected as the armor material, which are one of the promising materials for the plasma facing components in ITER. The armor tiles have a monoblock geometry with dimensions of 33 $mm^w \times 60$ $mm^t \times 30$ mm^l. Number of armor tiles is 24 and the interval between the armor tiles is 0.5 mm, that is, the total length of the armor is 730 mm. The annular swirl cooling tube is adapted in this mock-up. A shape of end-plug of the annular tubes have hemisphere with a radius of 7.5 mm, whose shape is determined from the pressure drop measurements. To mitigate thermal expansion along the cooling tube, a dovetailed sliding structure was applied for the support structure of the CFC armor.

To use CuCrZr as a cooling tube, optimization of the brazing process between the CFC armor and the CuCrZr cooling tube was performed to keep the mechanical strength. Because the mechanical strength of this material will be lower when it will be heated over an aging temperature, the bonding methods are restricted as following conditions, i.e., low temperature bonding lower than the aging temperature of 480°C or rapid cooling after brazing process at 1 K/sec [5]. As a result of preliminary test, mechanical strength of CuCrZr after the brazing process can be retained as high as the as-received material, which was provided by rapid cooling with Ar gas blowing in the cooling process from the temperature higher than 980°C followed by the aging process at 475°C for 2 hours.

2.3 High Heat Flux Tests

Thermal cycle experiments were performed under the heat load of 20 MW/m^2 for 15 s to simulate the ITER operational condition by means of an ion beam facility. In the thermal cycle experiment, an infrared camera was used to monitor the surface temperature profile. The coolant was purified water with an axial flow velocity of 10 m/s at an inlet temperature of 25°C.

Figure 5 shows the evolution of the surface temperatures of the armor tiles of the mock-up during the thermal cycle test. The surface temperatures of the armor tiles 14 and 15, which were located at the center of the heat flux profile, gradually decreased throughout

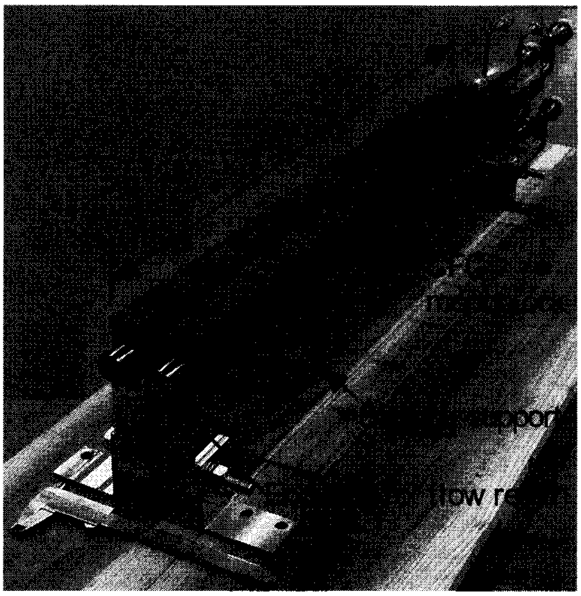

Fig. 4 Photograph of a large-scale vertical target mock-up

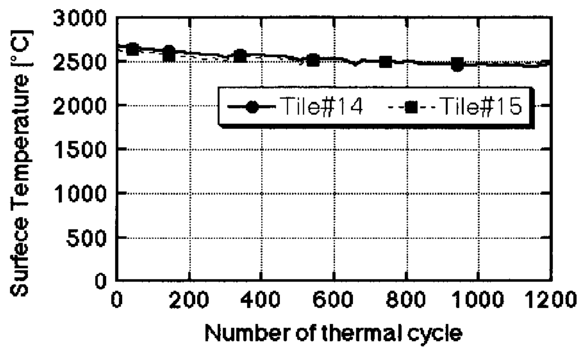

Fig. 5 Evolution of surface temperatures of the armor tiles of the mock-up

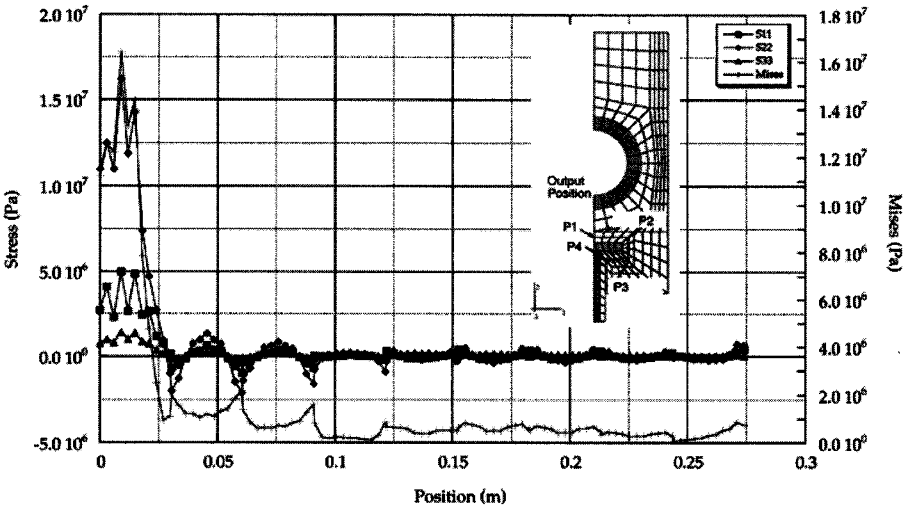

Fig. 6 Stress distribution along the cooling tube at P3

the thermal cycle test. Because thickness of the CFC armor decreased with proceeding the thermal cycle due to the sublimation, the thermal performance was enhanced apparently. From these results, it can be concluded that these armor tiles show no degradation of the thermal performance during the thermal cycle test up to 1000 cycles at 20 MW/m^2 for 15 sec.

2.4 Numerical Analysis

Numerical analysis was performed using a 3D finite element model as a reference for the experiment. Heat flux was assumed to have a Gaussian profile to simulate the experiments. The cooling conditions were also assumed as the same conditions as the experiments. To validate the efficiency of the slide support structure between the monoblock armor tile and the SS rail support, thermal-elastic analyses aimed at the CFC armor were performed.

Maximum surface temperature obtained from the analysis reached about 2900°C, which was about 400°C higher than the experiment. It was considered that surface temperature is kept by heat of sublimation, i.e., the sublimation of the CFC armor will begin from around 2500°C.

Maximum Mises stress of 16.4 MPa appears at P3 position, which is about 9 mm far from the beam center as shown in Fig. 6. It was found that this peak stress is about half of the ultimate tensile strength perpendicular to the fibers of CX-2002U and that the CFC dovetailed geometry for sliding support structure has enough margin for the divertor design.

3. Development of Joining Method of W Rod

JAERI has newly developed the W/Cu joining techniques; the W/Cu hot pressing method was adopted to improve the reliability and to reduce the cost. In this method, the W rods were used for armor material instead of the W plate to reduce the joining area. W rods are inserted into the corresponding holes on the Cu substrate by hot pressing. This W rod was made of the commercially available type W to reduce the cost.

To optimize the conditions of W/Cu hot pressing, several specimens were fabricated as the parameter of temperature and interface design. Tensile tests were performed to evaluate the mechanical properties of the specimens. As a result, the highest tensile load was

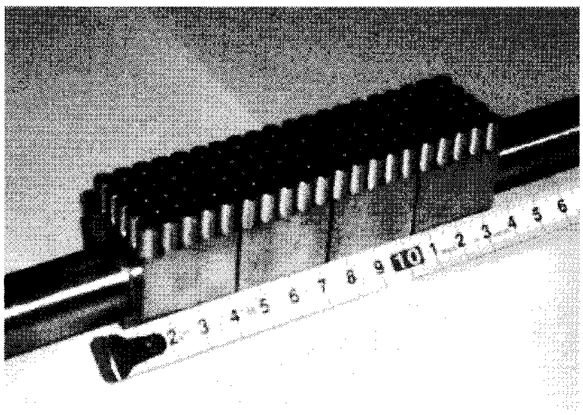

Fig. 7 The W rod hot pressing divertor mock-up

achieved with a W rod of one groove at the pressing temperature of 900°C.

Based on this result, a small mock-up for high heat flux test was fabricated to investigate the durability of the joining interface as shown in Fig. 7. For the thermal cycle test, the heat load of 5 MW/m^2 for 10 s was applied to simulate the ITER steady state conditions in the W covered region. The surface temperature showed almost constant value of 2000°C throughout 3,000 thermal cycles. In addition, no degradation of the thermal response was found through the experiments and any cracks were not found on the surface of the W rod after the experiments. Additional heating tests were also performed to evaluate the performance limit of the mock-up. The mock-up endured up to a heat load of 10 MW/m^2 for 15 s without failure. From these results, the hot pressing method is promising for W/Cu joint of the ITER divertor.

4. Conclusions

To increase reliability of the ITER divertor design, an annular swirl flow concept of the CFC monoblock with concentric feed and return has been developed. Thermal hydraulic tests were performed to measure critical heat flux of the annular swirl tube. As the result, no degradation of ICHF of the annular swirl tube was found in comparison with the conventional swirl tube.

Large-scale vertical target mock-up with an annular swirl tube was fabricated. In this mock-up, one-step brazing method was developed for joining the CFC armor and CuCrZr tube with an OFCu compliant layer. Thermal cycling tests were performed to clarify its thermal performance. The mock-ups have successfully withstood a heat load of 20 MW/m^2, 15 s for more than 1000 cycles, and it is demonstrated that the vertical target with the annular tube can be applicable to the ITER divertor plate.

The W/Cu hot pressing method has been also developed to improve the reliability and to reduce the cost. Thermal cycle test was performed on the W/Cu hot pressing divertor mock-up to investigate the durability of the joining interface. As the result, the surface temperature was almost constant throughout the experiment, and no degradation of the thermal response was found through 3000 cycles.

From these results, it was concluded that the new design for both lower and upper parts of the vertical target has capability of handling high heat flux, in addition, it can increase reliability and reduce manufacturing costs in comparison with the referenced design of ITER divertor.

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