Development of DEMO Divertor with Reduced Activation Ferritic/Martensitic Steel (F82H) in JAEA

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Abstract JAEA has been developing the DEMO divertor made of Reduced Activation Ferritic/Martensitic steel, F82H, which has been developed by JAEA. This paper reports recent three remarkable R&D achievements on the DEMO divertor: 1) High performance divertor cooling tube, so called a screw tube, made of F82H instead of Cu-alloy achieves 1.5 times higher incident critical heat flux (CHF) than a F82H smooth cooling tube, 2) Thermo-mechanical analyses reveal that a dovetail divertor support structure can reduce thermal stress by 30% in a cooling tube with a full scale divertor mock-up, 3) Hot pressing joint process for W pin armor concept has been modified to improve its heat removal capability against the high heat load. Using the newly developed technique, surface temperature of W pins can be kept lower than recrystallization temperature of W.

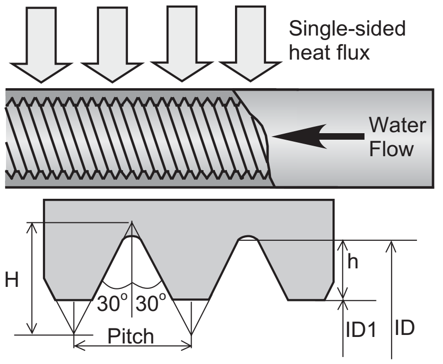
1. Introduction

In a design of a fusion DEMO reactor proposed by JAEA [1], divertor must handle high heat flux more than 10 MW/m^2 as well as the ITER divertor [2]. In the design, the divertor is cooled with pressurized water flowing in a cooling structure inside high heat flux components to match a coolant of the DEMO blanket. Accommodation of such high heat loads gives rise to several engineering issues affecting the performance and lifetime of the divertor components and influencing the selection of materials and configurations. This paper intends to report three of the R&D activities on the DEMO divertor in JAEA.

First is development high performance cooling tube. In the DEMO design, a cooling tube is made of Reduced Activation Ferritic Martensitic (RAFM) steel, F82H, is one of the candidate materials for the cooling tube of the divertor components instead of Cu-alloy that is used in ITER. As thermal conductivity of F82H is about 30 W/m/K, which is 1/10 of that of Cu-alloy, reduction of heat removal capability of the divertor cooling tube is envisaged. This study intends to examine a cooling tube with a helical triangular fin on its inner surface, so-called screw tube under divertor-relevant single-sided heating condition.

Second is development of support structure of the cooling tube. Since the divertor receives high heat load that causes severe thermal stresses in its cooling structure, it is one of the critical issues to develop a divertor support structure which can reduce thermal stresses. In our design the dovetail sliding support structure is adapted for the divertor. The effect on the relaxation of thermal stress on the cooling tube of the proposed support structure is experimentally and analytically demonstrated using a large-scale divertor mock-up.

Third is development of joint technology between different materials of the cooling structure and an armor tile that is made of a refractory material, tungsten (W). Tungsten is one of candidate materials for the armor material of the cooling structure from the viewpoints of its low spattering yields and low retention of tritium. For the DEMO divertor armor concepts, we have two options; one is tungsten monoblock armor, and the other is tungsten pin armor. In case of the tungsten pin armor concept, tungsten pins are bonded onto a heat sink. In this study, improvement of joint technology of this concept has been done and examined its heat removal capability against high heat flux condition.



Name	Pitch	H	ID	ID1	h
M10xP1.5	1.5	1.23	10	8.38	0.81

Figrure1 Schematic view of screw tube made of F82H

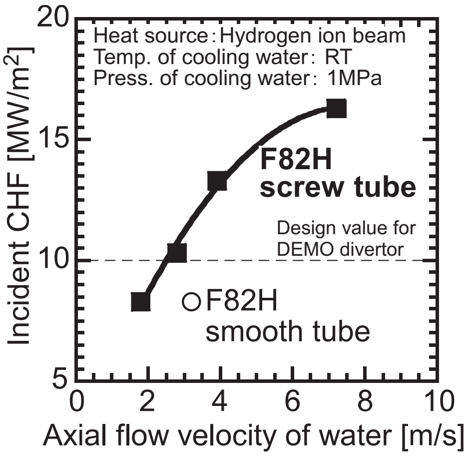


Figure 2 Incident critical heat flux (CHF) of F82H screw tube.

2. Critical heat flux of screw tubes made of F82H

High heat flux test on the screw tube made of F82H has been carried out using hydrogen ion beam to examine applicability of the screw tube to a DEMO divertor. Details of the screw tube are the present study shown in Fig. 1. The test sample is exposed to heat flux from a single side by the ion beam and is cooled with water flowing inside the tube at room temperature and at the pressure of 1MPa. The screw thread is directly machined in a F82H bare tube based on the ISO standardized metric screw thread of M10 type of 1.5-mm-pich, which can remove the highest heat flux in different geometries with screw tubes made of pure copper [3]. In the previous study, the screw tube made of pure copper showed twice higher incident critical heat flux (ICHF) defined at a component surface, which is one of indexes of heat removal limitation of a cooling tube, than a smooth tube[4] [5].

ICHF values of the F82H screw tube with M10 of 1.5-mm-pitch are plotted in Fig. 2 as a function of the axial flow velocity of cooling water. For instance, ICHF of the F82H screw tube is 13 MW/m^2 at the flow velocity of 4 m/s, which is about half value of that of the pure Cu screw tube at the same flow condition, i.e., 25 MW/m^2. However, this ICHF value of the F82H screw tube is 1.5 times higher than that of a F82H smooth tube. In addition, as shown in Fig. 2, at a flow velocity of 4 m/s, the F82H screw tube achieves 30% higher ICHF than the design value of the DEMO divertor.

One of the reasons of this ICHF reduction is ascribed to the lower thermal conductivity of F82H. To examine the effect of this advantage on the heat removal characteristics of the screw tube, heat conduction inside the tube wall have been analyzed with three-dimensional finite element model of the screw tube relevant to the experimental conditions. Heat transfer coefficient at the cooling wall of the screw tube used in this model is examined in the other experimental study [6]. Results of the heat conduction analyses of the screw tube model are shown in Fig. 3 that presents heat flux distribution inside the tube wall made of F82H and pure Cu at a heat flux value of 8 MW/m^2. The cooling conditions are the axial flow velocity of 4 m/s, the local pressure of 1

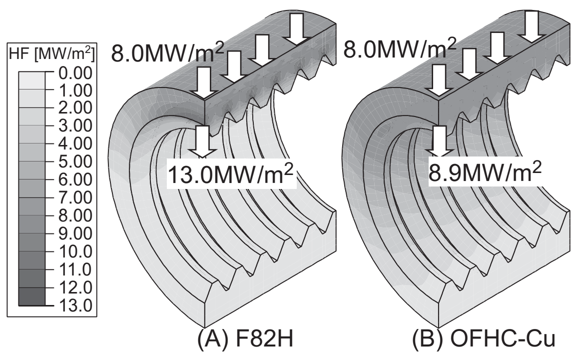


Figure 3 Heat flux distribution inside the screw tube with M10 thread of 1.5-mm-pitch made of F82H and pure Cu at 8 MW/m^2.

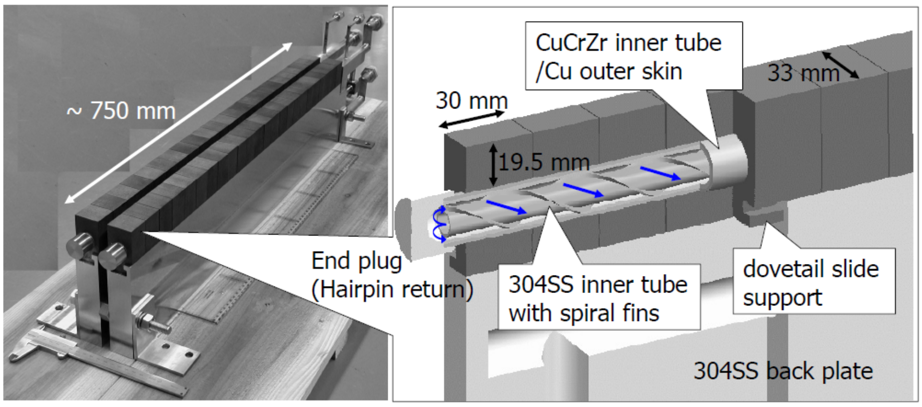


Figure 4 Schematic drawing and overall view of large-scale divertor mock-ups with a coaxial swirl tube.

MPa, and the coolant's bulk temperature of 36.5 ^{o}C based on the experimental condition. For the F82H screw tube, heat flow concentrates at the fin root of the tube top as shown in Fig. 3(A). In this case, the maximum heat flux is 22.1 MW/m^2, which is 1.7 times higher than the incident heat flux of 13 MW/m^2. On the contrary to this, heat flux concentration at the fin root of the pure Cu screw tube is less than that of the F82H case, that is, 1.2 times higher than the incident heat flux. This results from lower heat conduction of F82H. Therefore, heat flow inside the F82H tube wall cannot be dispersed around the tube wall like the pure Cu tube and concentrates at the tube top region. This leads the lower ICHF value of the F82H screw tube than that of the pure Cu tube. In the application of F82H to divertor cooling structures, therefore, enhancement of dispersion of the incident heat flow inside the components is necessary by some means, for example, being covered with armor material with higher thermal conductivity such as tungsten.

2. Effect of the dovetail support structure on thermal stresses in cooling tube

In the DEMO design of JAEA, the divertor will be exposed to a peaked heat flux of 10 MW/m^2. As this high heat load causes severe thermal stresses in its cooling tubes, it is one of the critical issues to develop a divertor support structure which can reduce thermal stresses. In our design the dovetail sliding support structure is adapted for the divertor, which is similar to that of ITER divertor. To confirm the effect of a dovetail support structure, a large scale divertor mock-up with a coaxial swirl cooling tube has been fabricated and tested under high heat flux conditions in JAEA. Figure 4 shows a schematic drawing of the mock-up [7][8]. The cooling tube made of Cu-alloy, CuCrZr is covered with the armor tiles made of Carbon Fiber reinforced Composite, CFC. The base of the armor tiles are machined to be a dovetail and are inserted into a channel of a backplate made of stainless steel. Figure 5 shows the maximum surface temperature evolution of the mock-up under a heat flux of 20 MW/m^2, in which the surface temperature is kept decreasing until about 1200th cycle because effective distance from the surface to the cooling tube is decreasing caused by continuous sublimation of the armor tiles. Although the armor tile suddenly cracked after those cycles, no damage in the cooling tube was observed. This can demonstrate the durability of the cooling tube with the dovetail sliding support against the repetitive high heat flux.

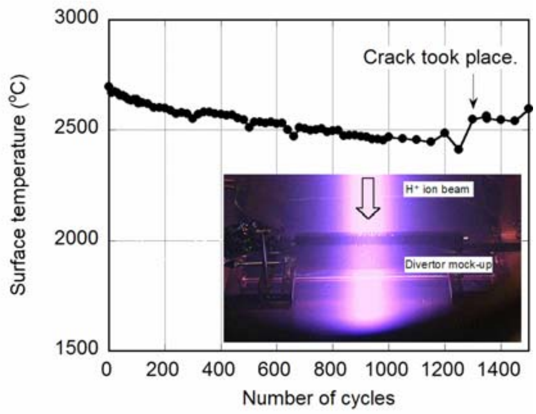


Figure 5 Maximum surface temperature evolution of the mock-up under the high heat flux condition of 20MWm^2.

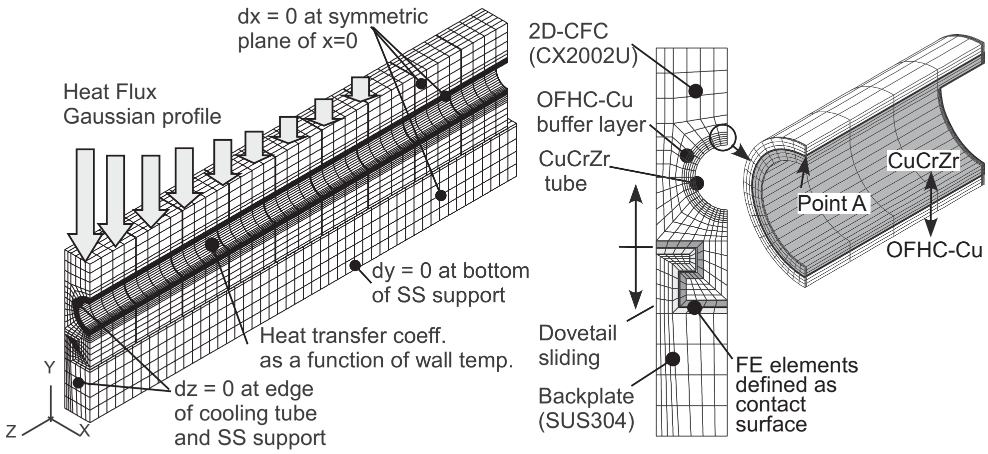


Figure 6. Three-dimensional FEM model and boundary conditions for thermo-mechanical analyses of a large-scale divertor mock-up with a dovetail sliding support.

To examine the effect of the dovetail sliding structure on the thermo-mechanical behavior of the cooling tube, thermal stress analyses have been made with a 3D FEM model using ABAQUS code [9]. The FEM model and its boundary conditions for thermo-mechanical analyses are shown in Fig. 6. The geometry of this FEM model stands for the design of the large-scale divertor mockup. In the simulation, thermal cycles are simulated to reach saturated stress-strain behavior. Based on the temperature evolution obtained in transient thermal analyses, subsequent elasto-plastic stress analyses are carried out. Prior to the simulation of thermal cycles, residual stress analysis is conducted to introduce into the model the initial stress strain and yielding after the braze cycle between the armor tiles and the cooling tube. The dovetail sliding support interface between the armor tiles and the backplate is treated as an adiabatic condition. In the mechanical analyses, no friction is imposed there, although geometrical contacts between them are taken into account in the mechanical analyses because the armor tiles made of carbon material is considered to not significantly obstruct thermal expansion or deformation of the cooling tube due to smoothness of its surface. Evolutions of temperatures of the armor tile surface and the cooling tube for three cycles at the heat flux of $20MW/m^2$ are shown in Fig. 7-(a). Based on these temperature histories, two cases of elasto-plastic analyses are carried out to examine the effect of the dovetail sliding structure on thermal deformation of the cooling tube. First is the model with the sliding support, in which time history of mechanical strain of the cooling tube at the axial direction, $\varepsilon_{mech,zz}$, is shown in Fig. 7-(b). The amplitude of $\varepsilon_{mech,zz}$ is close to saturated value of 0.25 % after the third heating and cooling cycle. Second case is the model without the sliding support.

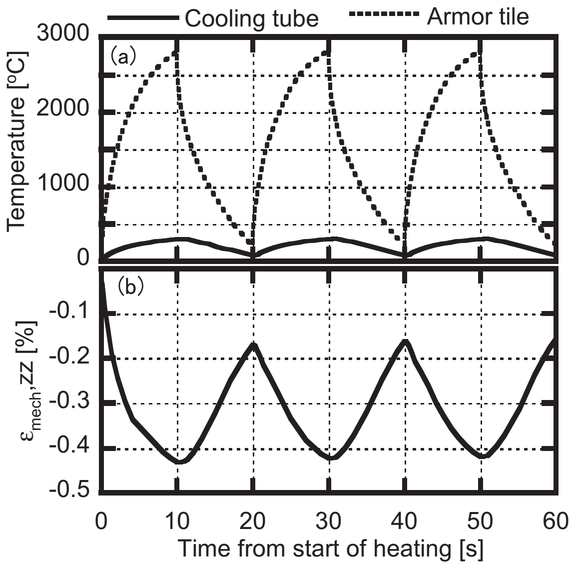


Figure 7. Evolutions of temperatures of the cooling tube and the armor tile and mechanical strain of the cooling tube in the axial direction, ε_{mech},zz, for three cycles at 20 MW/m^2 for 10 s.

Table 1. Comparison of the amplitudes of strain, $\Delta\varepsilon_{mech,zz}$, and stress, $\Delta\sigma_{zz}$, at the cooling tube in the axial direction.

	With dovetail support	Without dovetail support
$\Delta\varepsilon_{mech,zz}$ [%]	0.25	0.35
$\Delta\sigma_{zz}$ [MPa]	360	504

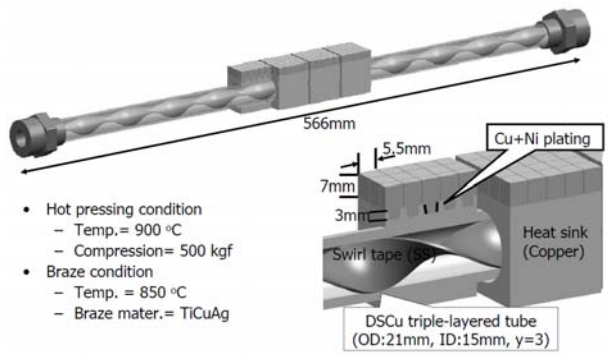


Figure 8. Schematic drawing of a divertor mock-up with pin-shaped tungsten armor.

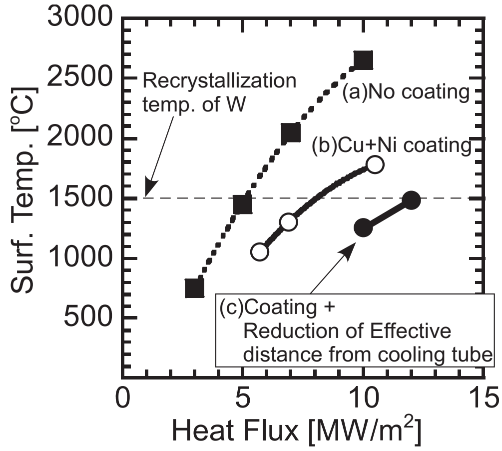


Figure 9. Comparison of thermal response of W-hot pressing mock-ups with different joining conditions in high heat flux experiment.

The amplitudes of the mechanical strain and the normal stress in the axial direction ($\Delta\varepsilon_{mech,zz}$ and $\Delta\sigma_{zz}$) in the both case are summarized in Tab. 1. It has been confirmed that the thermal stress in the cooling tube is reduced by about 30% by using the dovetail support structure compared to that without the dovetail.

3. Development of a new bonding technique for tungsten pin armor

For DEMO divertor armor concepts, we have two options; one is tungsten monoblock armor [10], and the other is tungsten pin armor. In case of the tungsten pin armor concept, tungsten pins of 5 mm squares are bonded onto a heat sink, such as Cu-alloy block. One of advantages of the pin armor concept is reduction of thermal stress at the joint interface caused by large mismatch of thermal expansion coefficients and elastic modulus of tungsten and a heat sink material. In the previous research we developed a hot press technique for bonding tungsten pins and the heat sink block made of pure Cu. In this activity, examination of anchoring effect of temperature and force during hot pressing process as well as taper-angle and number of groove of the W pin's root on the joint strength between the heat sink and the W pin was carried out through tensile test of hot-pressed W/Cu specimens and numerical analyses. Within the tested conditions, the geometry of the W pin's root with the taper-angle of 2.7^{o} and one groove and the pressing conditions of 900 ^{o}C and the compressive force 500kgf gave fracture strength at the joint as high as 90 MPa at 500 ^{o}C. The divertor mock-up fabricated using these hot pressing conditions was tested against the repetitive high heat flux as shown in Fig.8 [11]. Some pins were dropped after high heat flux tests. This results from low thermal conductance and ununiformity of contact between the W pins and the heat sink.

To recover these drawbacks of the joining with the hot pressing process a new bonding technique has been developed. In the newly developed technique, the tungsten pins' root are plated by Cu and Ni with the thicknesses of 2 μm first to improve adhesion of the W pins to the heat sink, and then hot-pressed onto the Cu heat sink block at around 900 ^{o}C. In addition to kept surface temperature of W as low as possible, effective distance between W pins' root and the cooling tube is reduced through reconsideration of geometry of the mock-up. Figure 9 shows three thermal responses of the divertor mock-ups with different W/Cu hot pressing and geometry of the joint in the high heat flux testing. After improvement of the joining process and geometry, the surface temperatures of the W pins decrease drastically. For instance, at the heat flux of 10MW/m^2, the surface temperature of W pins of the mock-up (c) with modified joint process is about half of that of the mock-up (a) with the original joint process, which is lower than recrystallization temperature of W. Numerical analyses show that the effective contact heat transfer coefficient is about 18 KW/m^2/K at the joint interface of the mock-up.

4. Concluding Remarks

In a design of DEMO reactor of JAEA, a divertor must handle high heat flux more than 10 MW/m^2. In the design, the divertor is cooled with pressurized water flowing in a cooling structure inside high heat flux components to match a coolant of the DEMO blanket. JAEA has been developing a divertor for DEMO reactors with Reduced Activation Ferritic /Martensitic steel, F82H. Through R&Ds activities, three remarkable achievements on the DEMO divertor has been done as follows; 1) High performance divertor cooling tube, so called a screw tube, made of F82H instead of Cu-alloy achieves 1.5 times higher incident critical heat flux (CHF) than a F82H smooth cooling tube, 2) Thermo-mechanical analyses reveal that a dovetail divertor support structure can reduce thermal stress by 30% in a cooling tube with a full scale divertor mock-up, 3) Hot pressing joint process for W pin armor concept has been modified to improve its heat removal ability against the high heat load. Using the newly developed technique, surface temperature of W pins can be kept lower than recrystallization temperature of W. Based on these encouraging results, the design of the tungsten-armored DEMO divertor with the F82H screw tube has started in JAEA.

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