Fusion Engineering and Design 85 (2010) 1255–1260

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Thermo-hydraulic testing and integrity of ITER Test Blanket Module (TBM) First Wall mock-up in JAEA

K. Ezato*, Y. Seki, H. Tanigawa, T. Hirose, D. Tsuru, H. Nishi, M. Dairaku, K. Yokoyama, S. Suzuki, M. Enoeda

Fusion Research and Development Directorate, Japan Atomic Energy Agency, 801 Mukoyama, Naka-shi, Ibaraki-ken 311-0193, Japan

ARTICLE INFO

Article history:
Available online 1 April 2010

Keywords:
Fusion reactor
ITER
Blanket
Test Blanket Module (TBM)
First Wall
Pebble bed

ABSTRACT

Fluid flow and heating tests on the full-scale Test Blanket Module (TBM) First Wall (FW) mock-up under the TBM-relevant operating condition were carried out in an ion beam irradiation system with a pressurized high temperature water loop in JAEA to verify the fabrication process and design of the TBM First Wall and demonstrate its heat removal capability. The TBM FW mock-up is made of reduced activation ferritic/martensitic (RAFM) steel, F82H, and its parts such cooling channels and plates were assembled with Hot Isostatic Pressing (HIP) method. In the fluid flow test, the cooling water at room temperature is supplied to 15 parallel flow paths in the mock-up. The flow distribution in each path inside the First Wall mock-up is compared with a numerical simulation. This result shows that no severe cross-sectional deformation of the entire flow path in the mock-up takes place during the fabrication process. In the heating test, the mock-up was exposed to repetitive hydrogen ion beam irradiation with the maximum heat flux of 0.5 MW/m^2. No indication of joint defect of the HIP joint like a hot spot was observed during 80 irradiation cycles.

1. Introduction

In a magnetically confinement fusion reactor such as ITER that is being built in France, under the international collaboration among seven parties including Japan, high temperature fusion plasma is confined in a vacuum vessel by using complex magnetic field. In ITER, to shield the vacuum vessel from the damage of heat and particle loads from the fusion plasma, plasma-facing components such as blanket and divertor are located at between the plasma and the vacuum vessel. The blankets cover the most of the surface of the vacuum vessel and the divertor is located at the bottom part of vacuum vessel. In ITER, two kinds of blankets are designed to be installed. The first is a shielding blanket that has functions to exhaust thermal energy generated by neutron from the plasma as well as surface heat load. The other is a Test Blanket Module (TBM) that is a prototype of breeding blanket being developed for the fusion reactor. This paper is intended to describe the recent R&D activities for TBM in JAEA.

The aims of the TBM program in ITER are to demonstrate the functions that the shielding blanket does not has as follows; one is to breed and recover tritium as a fuel for the fusion reactor and the other is to generate electricity [1]. The TBM program provides the first test stand to investigate these functions under the fusion environment of the world. Therefore, the parties joining this program are developing their own TBM design and requisite technologies relating their future fusion reactor design.

JAEA has proposed the TBM design with water-cooled structure and solid breeder (WCSB) concept as shown in Fig. 1 [2,3]. In this concept, a box frame made of reduced activation ferritic/martensitic steel, F82H, contains the multiple layers of pebble beds made of T-breeding material such as Li_2TiO_3 and neutron multiplayer material such as Beryllium. A First Wall (FW) which facing the core plasma directly is cooled with pressurized water. To maintain the surface temperature as uniform as possible, the parallel cooling square paths with a side of 8 mm are built into the F82H plate with 3 mm interval. The FW with the cooling paths and the box structure are integrated with a Hot Isostatic Pressing (HIP) process. The breeding and neutron-multiplying pebbles are packed into thin rectangular boxes separated by membrane panels with cooling tubes. These layers of the breeder and the neutron-multiplier zones are alternately arranged perpendicularly to the FW surface. Tritium generated in the breeder zones is recovered with helium purge gas flow. Since the nuclear heat generated inside the pebbles causes thermal expansion, thermo-mechanical interaction with the pebble bed and the structure should be investigated to evaluate the structural soundness of TBM. In addition, the pebble bed needs to be controlled its temperature below up to the upper limit of service temperature of the pebble bed material. Therefore, effective ther-

* Corresponding author. Tel.: +81 29 270 7554; fax: +81 29 270 7559.
E-mail address: Ezato.koichiro@jaea.go.jp (K. Ezato).

0920-3796/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2010.03.014

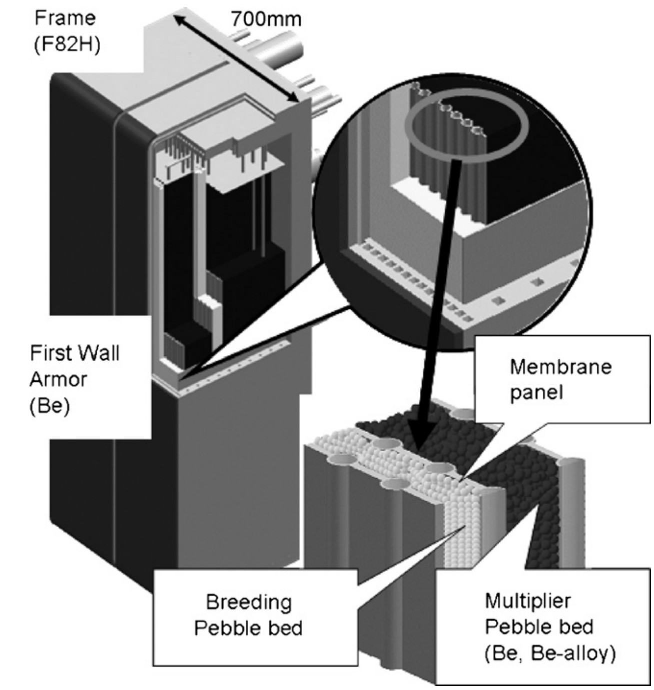

Fig. 1. Concept of TBM with solid-breeding and water cooled structure.

mal conductivities and strain–stress relationship of the pebble beds consisted of the breeding and neutron-multiplier material should be obtained and then modeled to integrate the thermo-mechanical analyses of the TBM structure. These effective values of the pebble beds affect the T-recovery behavior at the surfaces of the pebbles through the temperature profile inside the pebble beds. To evaluate the efficiency of the T-recovery, investigation of heat and mass transfer phenomena is one of the most importance issues.

From the viewpoint of the thermo-mechanical dynamics, one of the characteristics of TBM is cooling its box structure and FW by using pressurized high temperature water in the parallel flow paths. In the primary design, the coolant conditions are similar to the pressurized water reactor (PWR) conditions, that is, 15 MPa and 280 °C at the inlet of TBM. Flow distribution in the cooling channel in FW and heat removal characteristics under the single-sided heating condition are key point in the development of TBM as well as its integrity. JAEA has developed fabrication technology for TBM FW and its heating test is ongoing.

2. Fabrication of a near full-scale F82H FW mock-up

The FW is subjected to a highest heat load from plasma among in-vessel components except the divertor targets. The maximum heat load reaches 0.5 MW/m^2, which is comparative to a heat load of a reactor core of fission reactors. To remove this high heat load, the FW consists of an array of 15 cooling channels which are sandwiched by F82H thin plates as shown in a schematic drawing of the full-scale FW mock-up (Fig. 2). Manufacturing processes of the FW mock-up are as follows; as the first step, F82H circular tubes are fabricated by cold tube milling method. Their dimensions are 16 mm in an outer diameter, 1.5 mm in thickness, and 3.2 m in length. This F82H circular tube is deformed to a channel by cold rolling process. The fabricated F82H channel is 11 mm × 11 mm × 1.5 mm thick × 3.2 m long. A HIP method has been applied to bond these tubes and plates at the same time. The HIP conditions for F82H has already been developed using a small mock-up, the same conditions have been applied for the present mock-up; HIP temperature, pressure, and duration are 1100 °C, 150 MPa, and 2 h, respectively [4,5]. Fig. 3(a) shows the cross-sectional view of the mock-up and no deformation of the rectangular tubes is found. As each tube wall and plate are well HIPped, no bonding interface can be seen between the rectangular tube walls, and among the tube walls and the plate as shown in Fig. 3(b). In order to check deformation of the cooling tubes, the inside of each rectangular tube has been inspected through whole length by an optical fiber scope. Though some scratches are found on the inside wall of some tubes, no severe deformation has been found in all tubes. These scratches would occur during the cold rolling process of the rectangular tubes.

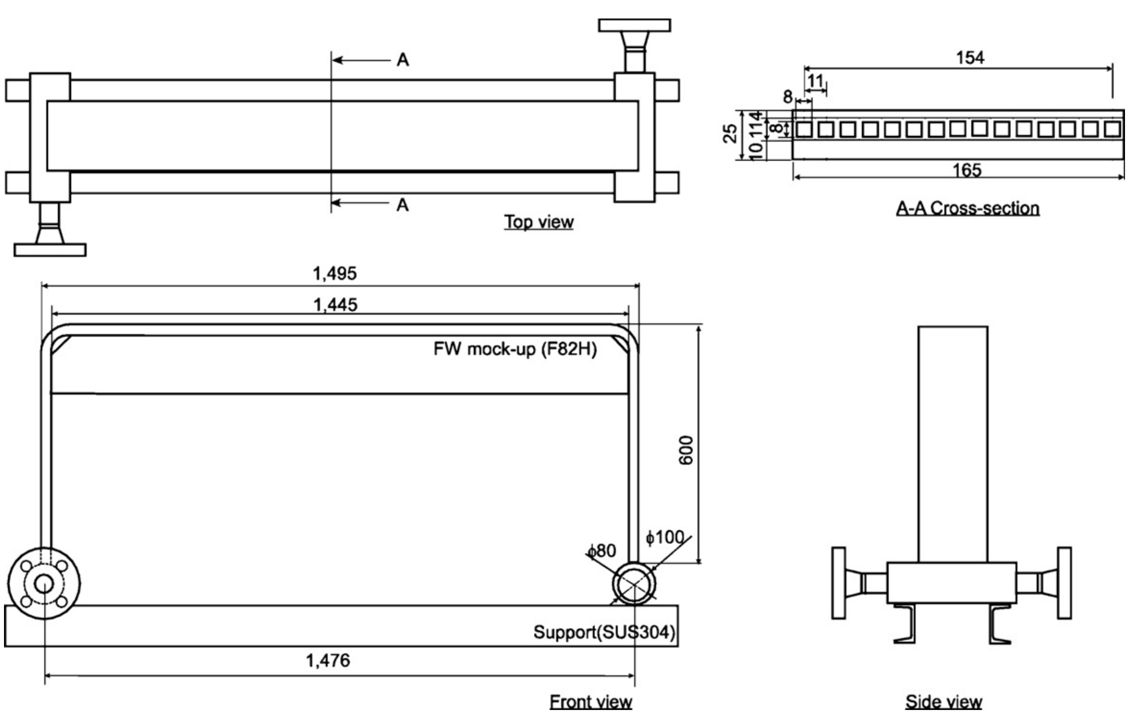

Fig. 2. Schematic drawing of full-scale First Wall mock-up.

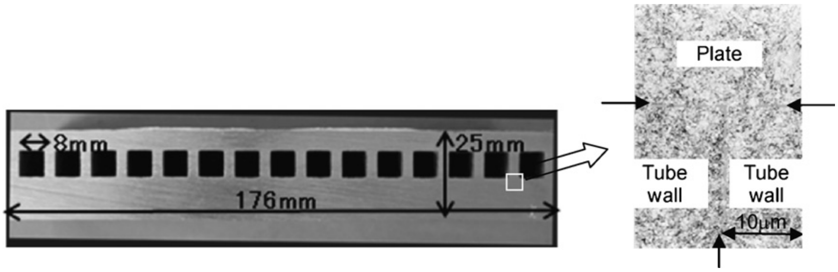

Fig. 3. (A) Cross-sectional view of the F82H FW mock-up, and (b) metallurgical observation.

Finally, manifolds and ribs are welded by tungsten-inert-gas (TIG) to the mock-up for high heat flux tests. The two rib panels simulate the sidewall of the TBM module box.

3. Measurement of flow distribution in the mock-up

Before the high heat flux tests, a flow distribution of the 15 cooling channels has been measured by an ultrasonic flowmeter. Cooling water conditions are as follows; 25 °C inlet temperature, 130 l/min inlet flow rate and 2 MPa inlet pressure. Fig. 4 shows an experimental setup. The total flow rate is measured with a turbine-type flowmeter that is connected to the inlet manifold. The ultrasonic flowmeter applied in the present measurement is originally used for the tube and the sum of the flow rate in the parallel flow paths in the FW mock-up cannot equal to the total flow rate measured with the turbine flowmeter. Therefore, the flow rate of each flow path measured with the ultrasonic flowmeter is normalized to the total flow rate. Fig. 5 shows the results of flow velocity distribution of 15 rectangular cooling tubes. In the parallel to the measurement of the flow distribution, in order to investigate the flow distribution in the FW mock-up under the experimental and TBM conditions, computational fluid dynamics (CFD) simulations with 3D model including the inlet and outlet manifolds for the coolant have been carried out by using FLUENT with low-Re k–ε turbulent model proposed by Abe et al. [6]. This turbulent model can deal with the complex coolant flow such as separation and re-attachment occurred in the manifolds. Fig. 6 shows an iso-velocity map in the plane at the centerline simulation under the experimental conditions. The average velocity in the each path is calculated and compared with the measurement in Fig. 5. The measurement of the flow velocity distribution shows a good agreement with the numerical estimation. It is confirmed that the difference of the flow rate is less than ±7% and that the flow paths were not deformed to affect seriously the flow distribution in the parallel flow paths. This means that the high pressure and temperature HIPping process was well performed.

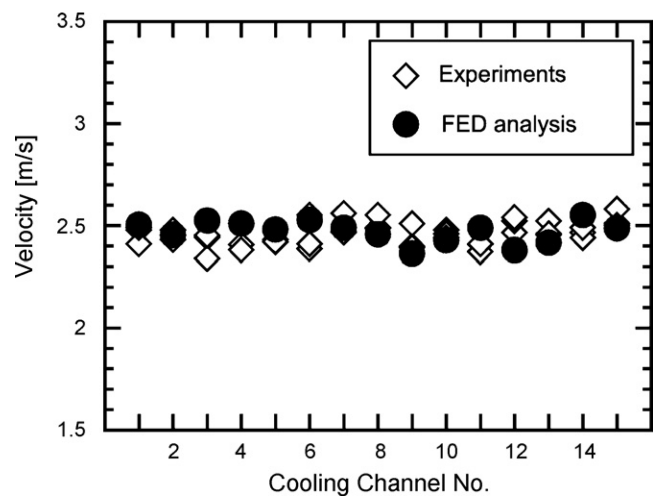

Fig. 5. Comparison of velocity in cooling channels between a numerical simulation and experimental data.

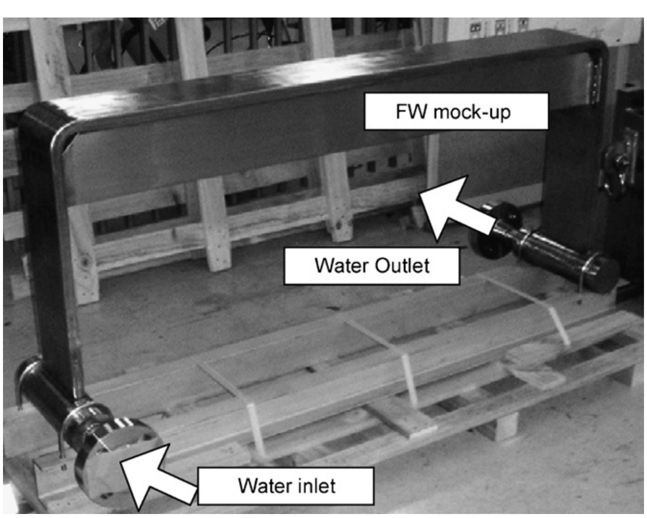

Fig. 4. Experimental setup for flow rate distribution.

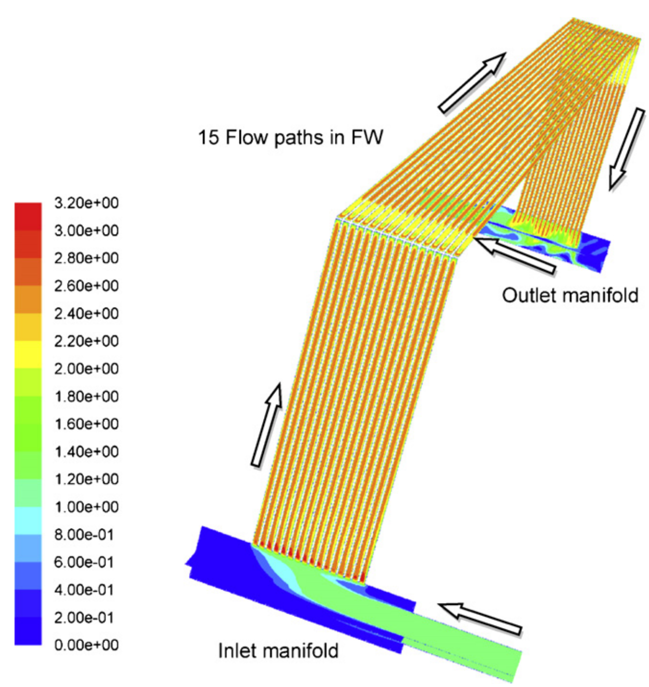

Fig. 6. Iso-velocity contour in 15 flow paths in FW.

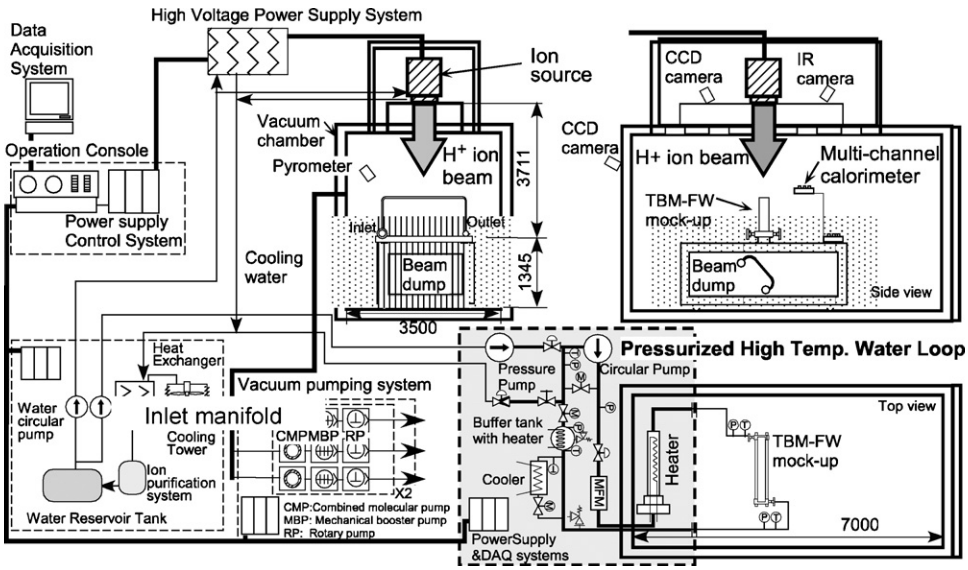

Fig. 7. Schematic drawing of Divertor Acceptance Test Stand (DATS).

Prior to the high heat flux testing, over-all deformation of the mock-up was measured during the pressurized water at 280 °C and 15 MPa flow in the mock-up. The measurement was carried out by using micro-scales monitored with CCD cameras remotely. It is confirmed that the maximum thermal deformation of the mock-up is less than 2 mm and this is no obstacle for the following high heat flux testing.

4. High heat flux tests on FW mock-up with pressurized high temperature water flow flowing

The Japanese WCSB TBM will be operated with an inlet temperature of 280 °C at a pressure of 15 MPa, which is almost the same as PWR conditions. A structural integrity is confirmed with such pressurized water cooling conditions at high temperature in a Divertor Acceptance Test Stand (DATS).

4.1. Experimental setup and test facility

The DATS facility in JAEA has been prepared for high heat flux testing on plasma-facing components such as ITER divertor targets and DEMO blankets FW. A schematic drawing of DATS is shown in Fig. 7. DATS can generate intense hydrogen ion beam up to 1.5 MW for duration from 0.01 to 1000 s. DATS consists of a vacuum chamber, an ion source and a test bed with pressurized water circulation. The ion source is mounted as a heat source at the top of the vacuum chamber. The ion source consists of a source plasma generator and an acceleration grid system. In the source plasma generator, hydrogen plasma is produced by an arc discharge process using tungsten filaments. Hydrogen ions are stably extracted by the acceleration grid system at the beam energy ranging from 16 to 50 keV with the beam current up to 30 A. In the present experiment, the FW mock-up is set at the test bed in the vacuum chamber to form a horizontal flow. The ion beam hits the center of upper surface of the FW mock-up.

The cooling water system has recently been upgraded to simulate the TBM and DEMO blanket cooling condition in which the pressure and temperature of coolant are 15 MPa and up to 400 °C, respectively. The coolant is pressurized by using a plunger-type three piston pressure pump and circulated by circular pump. The inlet temperature is heated by heaters in a buffer tank and in the vacuum chamber. After the test section, the coolant cooled by a cooler to keep a constant temperature during a cyclic additional heating by the ion beam.

4.2. High heat flux testing of FW mock-up and analyses

After the flow tests at high temperature, high heat flux tests on the mock-up have been carried out. As the first step, the coolant temperature is elevated to around 300 °C at 15 MPa, and then ion beams of a peak heat flux of 0.5 MW/m^2 is exposure onto the surface of the mock-up. The heat flux of the ion beam is measured with the array of calorimeter chips installed into the vacuum chamber. The heat flux profile is the Gaussian one with full-wise-half-maximum of 150 mm. The heating duration is 30 s.

Fig. 8 shows the near full-scale F82H FW mock-up during HHF testing in the DATS facility. Fig. 9 shows the infrared camera image during the tests. The maximum temperature appears to be 365 °C at the center of the ion beam. So far, 80 thermal cycles have been performed, and no degradation of temperature response and no hot spots have been found on the mock-up.

In parallel to the experiment, thermo-mechanical analyses using Finite Element Method (FEM) code, ABAQUS has been conducted. Fig. 10(a) presents the FEM model and boundary conditions for thermo-mechanical analyses. The FEM model is three-dimensional one and corresponds to 1/4 of the FW mock-up. In the thermal

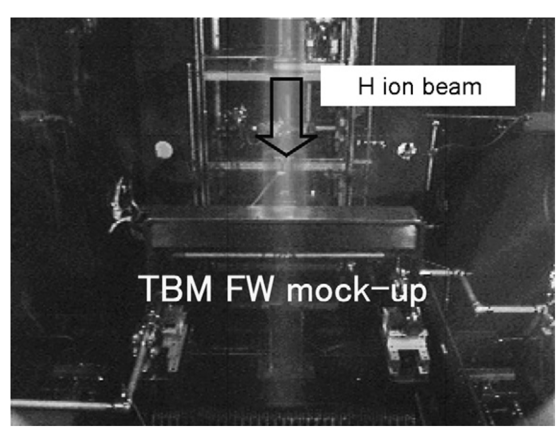

Fig. 8. FW Mock-up during high heat flux testing in DATS. Peak heat flux and its duration are 0.5 MW/m^2 and 30 s. Coolant conditions are 2 m/s, 300 °C and 15 MPa.

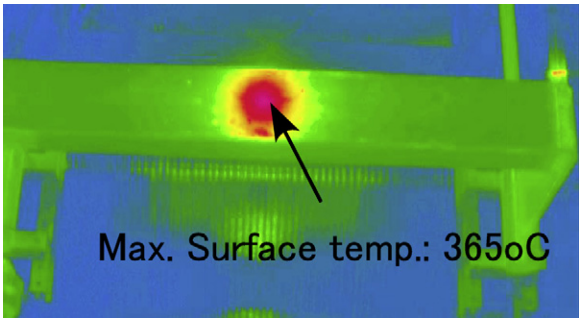

Fig. 9. IR image of FW mock-up during high heat flux testing.

analysis, the initial conditions of 280 °C as a coolant temperature and heat transfer conditions at the cooling channels are given by a function of the wall temperatures based on the Dittus–Boelter correlation with the coolant velocity of 2.5 m/s and the hydraulic diameter. Heat flux profile that is Gaussian simulate the measured value of the ion beam irradiation. The maximum surface temperature predicted by the FEM analysis shown in Fig. 10(b) is 380 °C at the end of the heating, which is a little bit higher than the experimental result mentioned above, although the temperature distribution is well predicted compared with Fig. 9. This discrepancy might be caused by the emissivity setting during the IR measurement. Using this temperature field, mechanical analysis has been carried out as shown in Fig. 10(c), in which, deformation of the mock-up during the heating test is presented with a scale factor of 200. The maximum von Mises stress occurs at the center of the surface of the mock-up that corresponds to the tem-

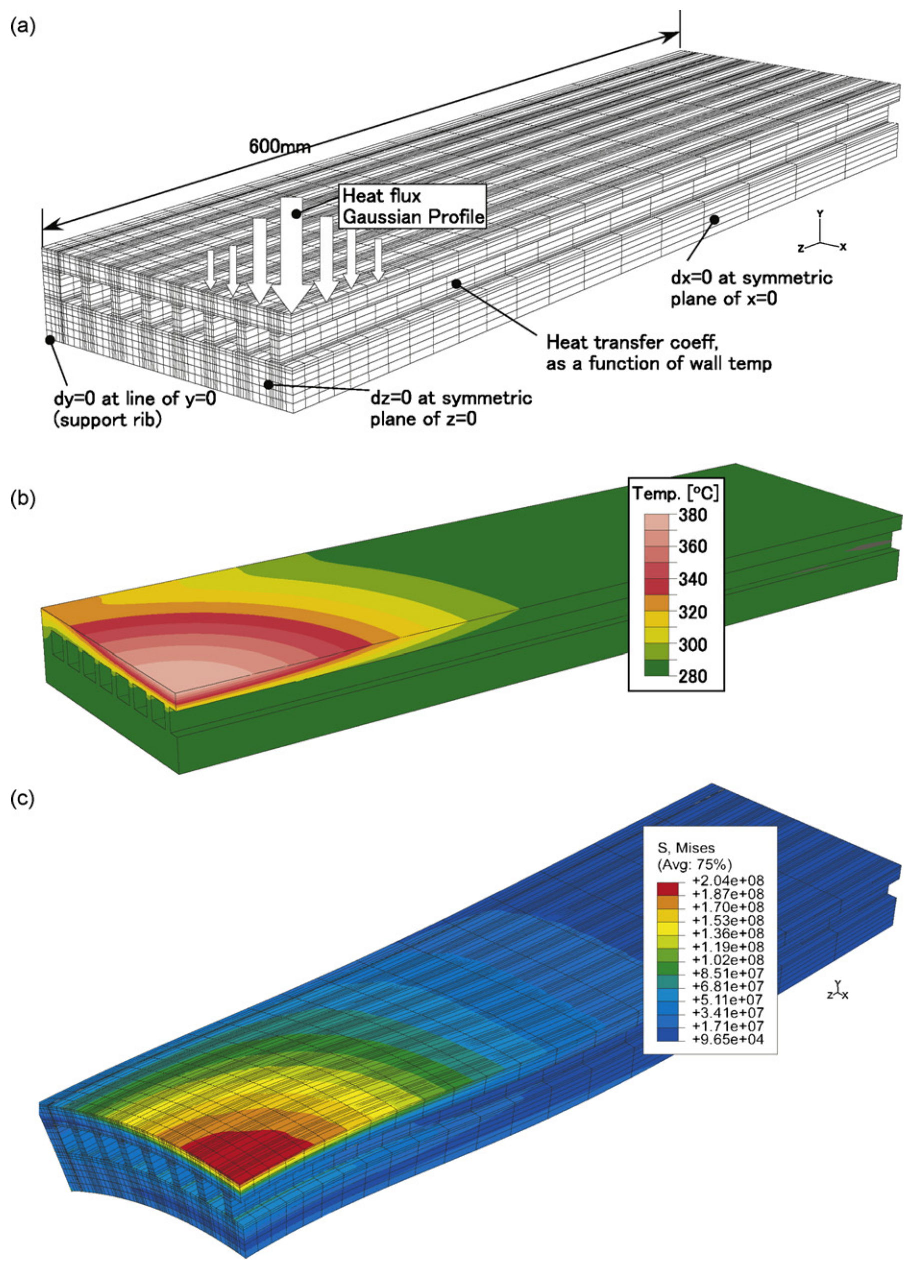

Fig. 10. Finite element model and analytical results. (a) FEM model and boundary conditions, (b) iso-temperature contour map at the end of heating under the experimental conditions, and (c) iso value contour map of von Mises stress with deformed scale factor of 200.

perature field. That value is 200 MPa, of which main component is compressive one in the *z*-direction (parallel to the flow channel direction), and whole of the model is within the elastic deformation. From this result, it can be presumed that the cooling channels and the front plate cannot be damaged except the bonding interface between the cooling channels and plates during the cyclic heating test. The later behavior will be examined after the further experiments, although the analysis shows the force tearing the bonding interfaces are small compared with the force in the *z*-direction.

5. Concluding remarks

The near full-scale F82H TBM FW has been successfully fabricated by using the HIP process. JAEA developed fabrication technology of F82H rectangular cooling tubes, and has successfully fabricated the near-full scale FW mock-up of WCSB TBM by HIP technique, which is fully made of F82H. The high heat flux test has been performed with the mock-up in the DATS facility in JAEA, which is an ion beam test facility. The inlet temperature of the cooling water is about 280 °C with 15 MPa, which is almost the same as the WCSB TBM design conditions. The mock-up has endured a heat load of 0.5 MW/m^2, 30 s for 80 thermal cycles. Neither hot spots nor thermal degradation has been observed. The CFD analysis reveals that the integrity of the FW mock-up, which will be demonstrated trough the further cyclic heating test.

Acknowledgments

The authors would like to express their acknowledgements to Dr. Akiba and Dr. Nishitani for their encouragement and support to conduct the present activities.

References

[1] L. Giancarli, V. Chuyanov, M. Abdou, M. Akiba, B.G. Hong, R. Laesser, C. Pan, Y. Strebkov, Breeding Blanket Modules testing in ITER: an international program on the way to DEMO, Fusion Eng. Des. 81 (2006) 393–406.
[2] M. Enoeda, M. Akiba, S. Tanaka, A. Shimizu, A. Hasegawa, S. Konishi, A. Kimura, A. Kohyama, A. Sagara, T. Muroga, Overview of design and R&D of test blankets in Japan, Fusion Eng. Des. 81 (2006) 415–424.
[3] Y. Nomoto, S. Suzuki, K. Ezato, T. Hirose, D. Tsuru, H. Tanigawa, T. Hatano, M. Enoeda, M. Akiba, Structural concept of Japanese solid breeder test blanket modules for ITER, Fusion Eng. Des. 81 (2006) 719–724.
[4] T. Hirose, K. Shiba, T. Sawai, S. Jitsukawa, M. Akiba, Effects of heat treatment process for blanket fabrication on mechanical properties of F82H, J. Nucl. Mater. 329–333 (2004) 324–327.
[5] T. Hirose, K. Shiba, M. Ando, M. Enoeda, M. Kaibab, Joining technologies of reduced activation ferritic/martensitic steel for blanket fabrication, Fusion Eng. Des. 81 (2006) 645–652.
[6] K. Abe, T. Kondoh, Y. Nagano, A new turbulence model for predicting fluid flow and heat transfer in separating and reattaching flows. I. Flow field calculations, Int. J. Heat Mass Trans. 37 (1994) 139–151.