Fusion Engineering and Design 86 (2011) 1693–1696

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

The KSTAR plasma facing components for 2010 operation

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ARTICLE INFO

Article history:
Available online 31 May 2011

Keywords:
KSTAR
Plasma facing components
Divertor
Passive stabilizer
Baking

ABSTRACT

The KSTAR plasma facing components (PFCs) consist of inboard limiter, poloidal limiter, divertor, passive stabilizer and neutral beam armor. The main function of the PFCs is to define boundary of operating plasma and to protect the vacuum vessel and in-vessel components such as diagnostic components, in vessel control coil and several kinds of launchers for heating and current drive systems. The divertor is designed to enhance effective particle control to keep high quality plasma with various flexibilities in the shaping control for wide range of operational regime. The passive stabilizer that is made of CuCrZr alloy is designed to passively control the vertical position and MHD instabilities during operation as well as outer boundary of the plasma. Since fabrication has been started for all of the plasma facing components from middle of 2009, the inboard limiter, the divertor, and the passive stabilizer were successfully installed in the vacuum vessel, in turn. Moreover, one set of neutral beam armor and three strings of poloidal limiters were also installed according to the heating system that newly comes in 2010. All the PFCs tiles were baked to 200 °C and the PFC system showed no vacuum leakage and other mechanical troubles. In this paper, key features, fabrication, results of assembly, and baking of the KSTAR PFCs are summarized in detail.

1. Introduction

In the first plasma operation and 2009 campaign of the Korea Superconducting Tokamak Advanced Research (KSTAR), inside of vacuum vessel was almost vacant except inboard limiter and poloidal limiter which was tentatively installed on the vacuum vessel to protect the ion cyclotron range of frequency (ICRF) antenna. The poor environment in the vacuum vessel caused one of the major limitations in the machine operation owing to the excessive particle recycling from the wall. Consequently, updating works for the in-vessel components is most urgent activity for the KSTAR operation. Moreover, KSTAR 2010 campaign mainly aims to achieve strongly shaped and diverted plasma with 2.0 of elongation (K) and 0.8 of triangularity (δ) that clearly requires divertor plates and several key devices for vertical position control [1].

Among various kinds of components and devices in the vacuum vessel, the PFC system has been fabricated and installed to meet the requirement of the 2010 campaign mentioned above. The PFC system includes inboard and outboard (poloidal) limiters, divertor, passive stabilizer that will play a role on controlling vertical position with help of active in-vessel control coil, and neutral beam (NB) armor to protect inside wall and components from the neutral beam.

2. Design feature

As shown in Fig. 1 that describes general configuration of the KSTAR PFC system, the divertor consists of inboard, central and outboard parts and is designed to achieve effective particle control to keep high quality plasma with enough shaping flexibility accommodating wide range of plasma operation. Each part comprises eight back-plates in upper and lower region, which are connected to each other plates to make a toroidal ring shape. The divertor has been designed for single-null (SN) and double-null (DN) operation modes, and the basic design requirement is that the actively water-cooled back-plate (or heat-sink plate) and the covering tiles that are made of carbon fiber composite (CFC) should accommodate 4.3 MW/m^2 of heat flux. However, graphite is one of the excellent candidates for the divertor tiles owing to low heat flux and relatively short pulse in phase I of the KSTAR operation which will be terminated by end of 2012.

The inboard limiter is a key component to protect inner wall of the vacuum vessel, and to define the inner boundary of plasma. Basic geometry of the inboard limiter has toroidally continuous cylinder shape covering straight section of the vacuum vessel. The inboard limiter comprises sixteen sectors according to the toroidal direction, which can be grouped as two sections: twelve normal

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doi:10.1016/j.fusengdes.2011.01.129

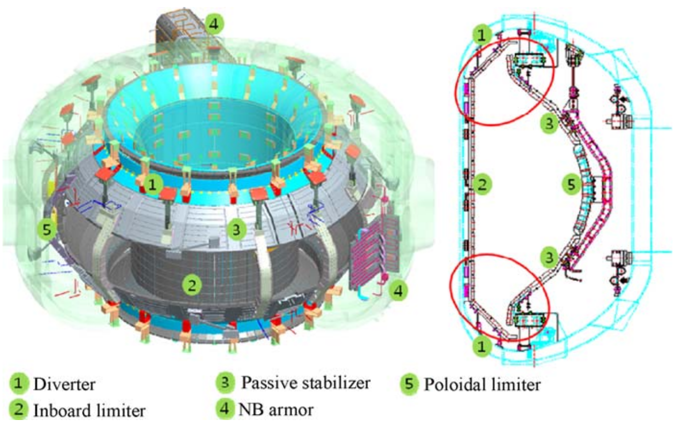

Fig. 1. Configuration of all PFCs. No. 1 is divertor including inboard, central and outboard divertor, No. 2 is inboard limiter, No. 3 is passive stabilizer including mechanical bridge and supports, No. 4 is NB armor including NB entrance port protector and NB shine-through, and No. 5 is poloidal limiter.

sections where graphite tiles are attached and four NB heating sections where CFC tiles are attached. However, the NB hitting section will be covered with graphite tiles due to the similar reasons described in the divertor. The tile material of the NB section will be replaced as CFC tiles when the NB injection (NBI) system operates longer than 20 s.

In addition to passive control of the plasma position, the passive stabilizer will play a role on control of magneto hydro dynamic (MHD) instabilities. The passive stabilizer has two toroidal ring-shaped plates with up-down symmetry. Each plate is composed of sixteen back-plates made of CuCrZr alloy, and forms a toroidally continuous ring with help of connection plates made of stainless steel 316LN. The CuCrZr alloy has excellent mechanical properties as well as electrical ones. Table 1 shows a chemical composition of the design and used material in the KSTAR tokamak. Table 2 shows important mechanical properties of CuCrZr alloy required and used in the KSTAR tokamak [2].

The baking and cooling (B&C) tubes are brazed on backside of the back-plate for the baking and cooling of the passive plates. All back-plates and connection plates are covered with the graphite tiles. Amount the sixteen-segmented plates, four plates can be grouped to a quadrant and each quadrant is mechanically supported by a connection plate in toroidal direction. Every quadrant is electrically isolated to each other, and is also electrically connected by resistors (called as gap resistor) to adjust the toroidal resistance. Upper passive plate is supported by 12 vertical and four upper horizontal supports, while the lower passive plate is mechanically connected and supported by nine mechanical bridges and four lower horizontal supports.

The NB armor consists of a NB entrance port protector and NB shine-through armor, and the graphite tiles are attached for the armors. The NB entrance port protector is for the protection the vacuum vessel port from the particles occurring by interactions between energetic particles in the neutral beam and background neutral particles in the port area. The opposite side surface of the NB entrance port can be damaged by neutral beam penetrating the plasma area, therefore, the NB shine-through armor is designed to prevent damage on the surface of inside the vacuum vessel.

The poloidal limiter is installed to protect the ICRF and the lower hybrid current drive (LHCD) antennas against energetic particles come from the plasma. The poloidal limiter contains totally three poloidal strings having parabolic shape with the graphite tiles, and is installed on the mechanical bridge of the passive stabilizer. Table 3 shows more detail explanation for the composition and material of the KSTAR PFC system in 2010 KSTAR campaign.

Table 4 summaries the maximum value of the heatflux on the PFC's back-plates during the KSTAR plasma operation.

Table 3
Material of KSTAR PFCs.

Components	Tile	Back-plate
Divertor	Graphite	SA240-316LN
Inboard limiter	Graphite	SA240-316LN
Poloidal limiter	Graphite	SA240-316LN
Passive stabilizer	Graphite	CuCrZr
NB armor	Graphite	SA240-316LN

Table 4
Maximum heatflux of KSTAR PFCs.

Components	q_{max} (MW/m^2)	Type	
Divertor	Inboard	4.3	Non uniform
	Central	4.3	Non uniform
	Outboard	0.69	Non uniform
Inboard	NB hitting	2.3	Non uniform
limiter	Normal	0.33	Non uniform
Poloidal limiter	1.7	Uniform	
Passive stabilizer	0.37	Uniform	
NB armor	0.7	Uniform	

3. Fabrication

The back-plates of the PFCs are manufactured through a complicated process at the shop. After the detail drawing of the PFCs is completed, an inspection of material and a machining process with press and bending process are progressed. And then, a welding between back-plate and cooling cover and inspection of welding regions proceeds in order. The nondestructive test such as a radiation test (RT), penetration test (PT) and ultrasonic test (UT) is performed at the welding parts according to ASME section VIII division 1. The size of fault at the welding parts is allowed less than 50% size of ASME code and there must be no scales at the vacuum surface [2].

Table 1
Chemical composition of CuCrZr alloy (weight%).

Composition	Cu	Cr	Zr	Other elements
Design material	98.7 min	0.4–1.2 nom: 0.8	0.08–0.2 nom: 0.14	Max 0.2
Used material	99.2 min	0.61	0.13	–

Table 2
Mechanical property of CuCrZr alloy (@ 25 °C).

	Mini.tensile strength (s_u) (MPa)	Mini.yield strength (s_y) (MPa)	$1/2s_u$ (MPa)	$2/3s_y$ (MPa)	Design stress intensity (s_m) (MPa)
Required	413.1	297.3	206.6	198.2	198.2
Used	413.9	357.1	207	238.1	207

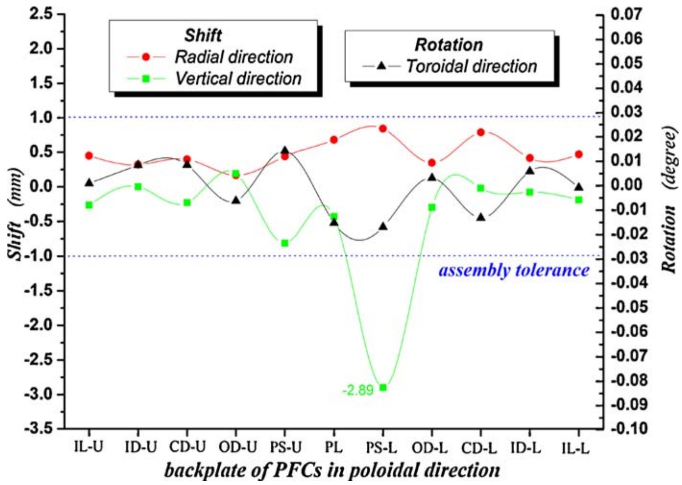

Fig. 2. Assembly results of all the back-plates; IL: inboard limiter, ID: inboard divertor, CD: central divertor, OD: outboard divertor, PS: passive stabilizer, PL: poloidal limiter, U: upper, L: lower.

After the final machining of the back-plate, the heating test, pneumatic test, and helium leakage tests were fulfilled according to the test sequences. The heating test was the leakage inspection of the back-plate and tube that were baked to 350 °C for 10 min, and pressurized by 15 bars using nitrogen gas. After the heated back-plate is cooled down by room temperature in air, the pneumatic test is performed by fifteen bar using nitrogen gas. All welding points of the back-plate were checked by helium leakage detection in vacuum tightness. The sensitivity of the helium detector keeps lower than 5.0×10^{-10} mbar l/s in the leak rate. For final process of the fabrication, electrolytic polishing and final inspection were performed to complete a back-plate.

4. Installation

There were four steps for installation of the PFCs in the vacuum vessel; the first step was to exactly install several kinds of pads on the surface of the vacuum vessel by with three-dimensional survey, following second step was to set up back-plates on the pads after the three-dimensional measurement, the third step was to connect the channel of the back-plate to the manifold, and finally attach the graphite tiles on the back-plates.

It is very important for the PFCs to be exactly installed in the vacuum vessel because the PFCs define the boundary of the operating plasma. Consequently, an optical metrology system such as the laser tracker was mainly utilized for survey and alignment of the back-plates. The aligning system of the KSTAR PFCs used the Tracker 3 (T3) of the API (Automated Precision Inc., USA). The accuracy of the T3 system is less than 10 ppm [3].

The cylindrical coordinates system has been principally used in the alignment of the PFCs and the rectangular coordinates system has been partially used in the adjustment of the back-plates. There are four or six fiducial points which have been machined on the back-plate in the fabrication process, these fiducial points played an important role on the alignment of the back-plate. Because the fiducial points represent the shape and location of the back-plate, the alignment and adjustment of the fiducial points was to arrange the location of the back-plate in the vacuum vessel.

Fig. 2 shows an assembly result of the back-plate of the PFCs in the poloidal direction. The result illustrates the deviations between the center point of each back-plate and that of the KSTAR tokamak. The allowable assembly tolerance of the vertical and radial direction is ±1.0 mm and the allowable angle of the toroidal direction is ±0.03°.

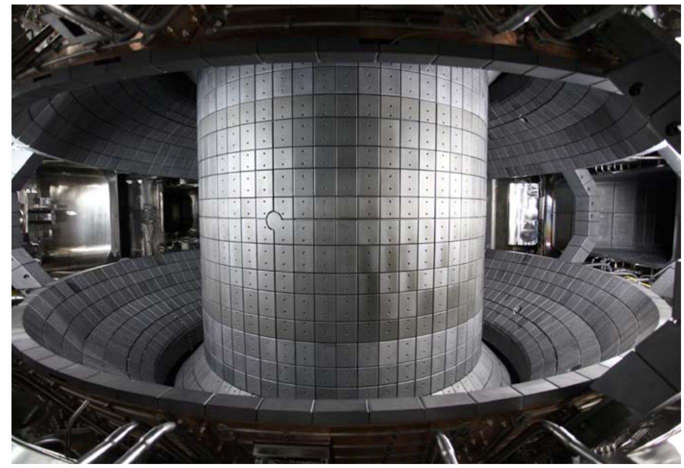

Fig. 3. Inside of vacuum vessel after finish in the installation of the PFCs.

All the components except for the lower back-plate of the passive stabilizer have been aligned within the allowable assembly tolerance. The deviations for the vertical direction at the lower back-plate of the passive stabilizer exceeded the allowable tolerance by 1.89 mm. This result at the lower back-plate of the passive stabilizer mainly stemmed from connection mechanism that lower plates of the passive stabilizer are connected to upper plates and supported by nine mechanical bridges. Although the assembly tolerance is exceeded at the lower back-plate by 1.89 mm, because the difference value of the radial direction is lower than the assembly tolerance, we convince that it is not a big problem in the plasma operation and to define the boundary of operating plasma. Fig. 3 shows inside of the vacuum vessel after all the PFCs, and in-vessel components were installed.

5. Baking [4]

Two groups of the B&C pipe system for all the PFCs were installed in the vacuum vessel to fulfill baking and active cooling of each PFC. The first group (called group A) comprises top and bottom B&C lines including inboard, central and outboard divertor. Another group (called group B) contains upper and lower B&C lines including inboard limiter, passive stabilizer with connection plate and mechanical bridge, NB armor, and poloidal limiter. The B&C system of the PFCs was basically designed to be baked the graphite tiles by 300 °C while the vacuum vessel is maintained at about 130 °C. However, owing to the technical troubles in the hot nitrogen gas supply system, and owing to the machine cool-down that requires the vacuum vessel to be kept at room temperature, the baking temperature of PFCs was limited to 200 °C in 2010 campaign. More than two hundreds of thermocouple (NiCr–Ni, K type) have been installed in the graphite tiles at 5 mm behind the surface. All the sensors provide a basic tool for the temperature control on every PFC through real-time monitoring of the temperature on tiles and structures. Table 5 shows several key parameters of the gas flow, and tube layout for each PFC during PFC being kept at room temperature (30 °C) with 5.3 bar.

Fig. 4 shows the baking results of the PFCs in 2010. The surface temperature of the graphite tiles was increased from room temperature to 200 °C for more than 6 days. The increase rate of temperature was controlled from 3 °C to 5 °C per hour. When the supplying pressure of nitrogen gas was raised to about 5 bars, the partial pressure of mass number 28 (N_2 or CO) was maintained within allowable value, of which result shows no detectable nitrogen leakage from the B&C lines.

Table 5
Gas flow parameters and tube layout for each PFC.

Flow parameter	ID	CD	OD1OD2	IL	PS
Velocity (m/s)	7.0	5.4	8.8	19.3	17.4
Mass flow (per channel, g/s)	6.9	5.0	8.06.2	17.0	8.4
Total mass	554	554	554	273	536
Pressure drop (bar)	0.03	0.012	0.032	0.149	0.033
Tube inner diameter (mm)	7.3	7.0	7.06.1	13.8	10.2

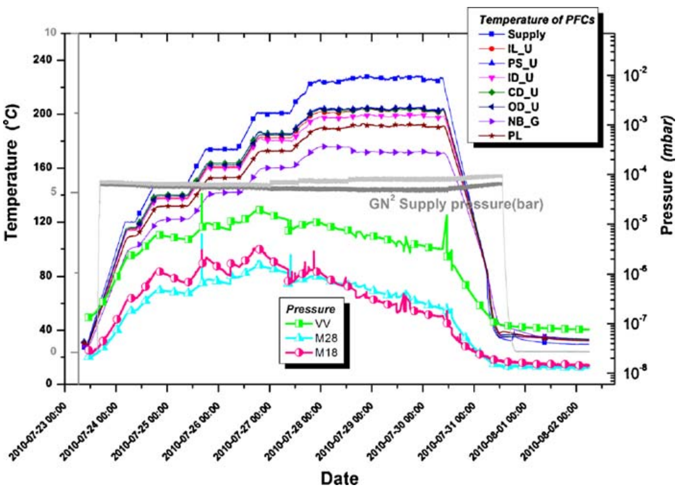

Fig. 4. Baking result of PFCs in 2010 operation.

After PFC baking, the vacuum pressure has been decreased from 1.35×10^{-7} mbar to 7.73×10^{-8} mbar, and the partial pressure of mass number 18 (H_2O) was decreased from 2.5×10^{-8} mbar to 1.5×10^{-8} mbar, of which result shows again that the PFC B&C lines have been successfully installed with satisfying tight requirement of the vacuum commissioning.

6. Conclusion

All the PFCs including the B&C lines have been successfully installed in the vacuum vessel by June 2010. However, the divertor and poloidal limiters are to be majorly upgraded in addition to partial change at the inboard limiter in the future, when the performance of the KSTAR is substantially improved and the pulse length of the plasma will be extended to longer than 20 s.

The temperature of the graphite tile has been increased to 200 °C for more than 6 days of baking operation. The increase rate of temperature was controlled within relatively slow (3–5 °C per hour) to prevent mechanical damages excessive temperature variations between neighboring structures. The PFC baking was proved to be quite effective for water removal both in the vacuum vessel and in the graphite tiles. The partial pressure of the nitrogen, which was maintained in relatively lower pressure showed a clear evidence that the PFC B&C pipe system was installed without vacuum leak.

Acknowledgment

This work is supported by Ministry of Education, Science and Technology of the Republic of Korea under the KSTAR project contact.

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