Design, fabrication and testing results of vacuum vessel, thermal shield and cryostat of EAST

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Abstract.The EAST (Experimental Advanced Superconducting Tokamak) is an advanced steady-state plasma physics experimental device, which has been approved by the Chinese government and being constructed as the Chinese national nuclear fusion Research project. The vacuum vessel as one of the key components for this device can provide ultra-high vacuum and cleanly location of plasma operation. It is a torus with "D" shaped cross-section, double wall, upper vertical ports, lower vertical ports, horizontal ports and flexible supports. The cryostat is a large single walled vessel surrounding the entire basic machine with central cylindrical section and two end enclosures, a flat base structure with external reinforcements and dome-shaped lid structure. It provides the thermal barrier with the base pressure of 5×10^{-4} Pa between the ambient temperature testing hall and the liquid helium cooled superconducting magnet. The thermal shields comprise the vacuum vessel thermal shield (VVTS), between the vacuum vessel and the cold Toroidal Field (TF) coil structures, the cryostat thermal shield (CTS), covering the walls of the cryostat, thereby preventing direct line of sight of the room temperature walls to the cold structures, the vacuum port thermal shields (VPTS) that enclose the port connection ducts. This paper is a report of the structure design and stress analyses for the vacuum vessel, thermal shield and cryostat. And also some key R&D and testing results for these components have been presented.

1. Introduction

The EAST (Experimental Advanced Superconducting Tokamak) is an advanced steady-state plasma physics experimental device, which has been approved by the Chinese government and being constructed as the Chinese national nuclear fusion Research project. The assembling was finished by the end of 2005 and the first commissioning started from Feb.1 ,2006 and finished on March 30,2006 at the Institute of Plasma Physics, Hefei, Anhui, China(ASIPP). It consists of leakage testing at room temperature and low temperature, pumping down, cooling down for all coils, current leads, bus bar and the thermal shielding, exciting all the coils, magnetic configuration measurement and magnets warm up. As one of the key components for the device the vacuum vessel can provide an ultra-high vacuum and cleanly location for the operation of plasma. During it operation the vacuum vessel will not only endure the electromagnetic force due to the plasma disruption and Halo current but also the pressure of boride water and the thermal stress owing to the 250℃ baking out by the hot pressure nitrogen gas or the 100℃ hot wall during plasma operation. The cryostat is a large single walled vessel surrounding the entire basic machine with central cylindrical section and two end enclosures, a flat base structure with external reinforcements and dome-shaped lid structure. It provides the thermal barrier with the base pressure of 5×10^{-4} Pa between the ambient temperature testing hall and the liquid helium cooled superconducting magnet. The thermal shields comprise the vacuum vessel thermal shield (VVTS), between the vacuum vessel and the cold TF coil structures, the cryostat thermal shield (CTS), covering the walls of the cryostat, thereby preventing direct line of sight of the room temperature walls to the cold structures, the vacuum port thermal shields (VPTS) that enclose the port connection ducts. The thermal shields are made of double-wall panels, sandwich structure consist of two stainless steel panels and weld quadrate cooling pipe in it[1].

2.Design of vacuum vessel, thermal shield and Cryostat[2,3]

The vacuum vessel is the location for the operation of plasma as one of the key component for EAST superconducting Tokamak device. According to the EAST physical design, the yield of neutron during high parameters deuterium-deuterium (D-D) operation of EAST is $S_n=1\times10^{15}$ n/s. The average energy of D-D neutron is 2.45MeV. In addition the neutron produced from deuterium, few neutrons with energy of 14 MeV will be produced by deuterium-tritium reaction. So a double-shell vacuum vessel was proposed and designed. The space between the two shells of the vacuum vessel will be filled with borated water in 100°C that is affected as shield during D-D operation. The shield water is borated with 22 grams per liter of boric acid, considering the resolvability of boron and corrosion to the vacuum vessel material of 316L stainless steel. The vacuum vessel is a fully welded toroidal structure with noncircular cross-section nested in the bore of the TF coils.Overall exterior dimensions of the vacuum vessel are 2.63m in height with the inner radius of 1.95m and the outer radius of 2.75m. The thickness of the inner and outer skins is 8mm. The torus consists of 16 segments and each segment consists of inner shell, outer shell, ribs and ports. Two toroidal ribs separate outer shell and inner shell, and give the required mechanical strength. The ribs welding to inner and outer shells are skipping welding. Other two ribs (end ribs) are welded both to inner shell and outer shell tightly at segment end. Every two segments are welded together by end ribs. On the vacuum vessel totally there are sixteen horizontal ports and thirty-two vertical ports. With physical diagnostics and test specifications, three types horizontal ports and four types vertical ports with different shapes and size were needed. One of them is capable for tangential neutron beam injection and physical diagnostics. The effective aperture of the tangential port is 970mm×528mm. Prior to operation the vacuum vessel is to be baked out and discharge cleaned at about 250°C in order to get an ultra-high vacuum and a cleanly environment for plasma operation. The 350°C hot nitrogen gas is used for the methods of vacuum vessel baking and the electrical heater is used for the baking of the ports. Due to the non-uniformity of temperature distribution on the vacuum vessel owe to the difference of heaters distribution and velocity of nitrogen gas will bring about expansion movement and serious thermal stress of the structure. Considered this factor and manage to reduce the rigid of structure during the stage of design, a kind of low rigid structure support system is designed and on each port necks there are two bellows section, which allow the vacuum vessel slight moveable in radial direction. This kind of structure can accommodate thermal deformation and small displacement caused by bake-out and other reasons so that it can protect the device. Fig.1 has shown the structure of EAST vacuum vessel.

The thermal shields comprise the vacuum vessel thermal shield (VVTS), between the

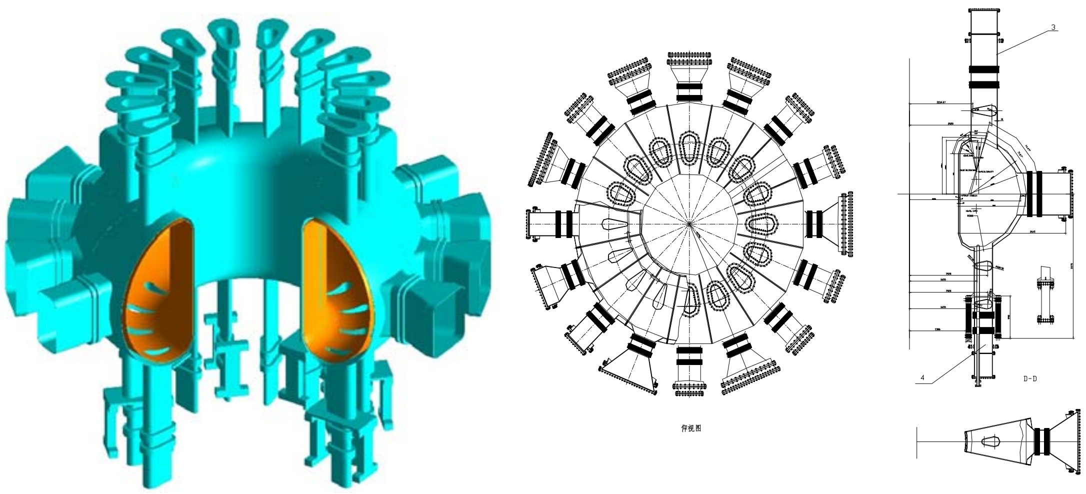


FIG.1.The Struture of Vacuum Vessel

vacuum vessel and the cold structures, the cryostat thermal shield (CTS), covering the walls of the cryostat (bottom, cylinder and upper head), thereby preventing direct line of sight of the room temperature walls to the cold structures, the vacuum port thermal shields (VPTS) that enclose the port connection ducts. The VVTS has to closely follow the shape of the VV, for space reasons, and is therefore of a segmented, toroidal design. It is composed by 14 of 22.5° sectors and 4 of 11.25° sectors. The sectors are connected each other during assembling to form a D shape cross-section torus to enclose the vacuum vessel. The CTS is divided into three parts: upper cap, middle cylinder and bottom platform. Each part of CTS consist of 8 octants. The VVTS and CTS are connected each other by the 16 horizontal VPTS and 32 up and bottom vertical VPTS to form a rigid self-supporting structure under its own gravitational and thermal loads and is attached to the bottom of cryostat by 4 inboard and 8 outboard supports. The inboard and outboard supports are stainless steel multi-plate type structure, which is allowing radial movements. The space envelope is particularly critical for the VVTS. The gap between the VV and the TF coils, in which the VVTS resides, needs to be kept as small as practical. A considerable effort has therefore been expended on keeping the design of the VVTS as slim as possible. Therefore, in all cases the thermal shields are made of double-wall panels, sandwich structure consist of two stainless steel panels and weld quadrate cooling pipe in it or strength reasons and additionally for reducing the radiant heat loads on the magnet structures without overly complicating the cooling tube layout, by interception of heat loads from panels facing the VV and keeping the panels facing the coils relatively cold. The thermal shields are cooled by helium gas with 57K inlet temperature. The cooling lines remove the heat load intercepted from the warm surfaces. The cold magnet structures, operating around 4K, face the TS surfaces only. To minimize the heat load received from the warm surfaces and to reduce the heat load radiated to the 4K surfaces, the thermal shield panels are polished. While the thermal shields perform no safety function, their repair or replacement, particularly of the VVTS, would involve dismantling major parts of the TF magnet, VV and other in-cryostat components. Therefore, the thermal shield is conservatively designed to withstand any loads without damage. Further enhancements against failure and magnetic penetration are obtained by having electrical breaks incorporated in VVTS sector joints, reducing the electromechanical loads on the structure.Fig.2 have shown the structure of EAST thermal shields.

The cross section of EAST cryostat is shown in Fig. 3 with the outline of the tokamak machine. The cryostat consists of a cylindrical section bolted to dished lid wall at top and to base plate at bottom by flanges with special C clamps of diameter 40mm. The lid wall of the cryostat is a dished configuration for reasonable stress distribution. The support of cryostat

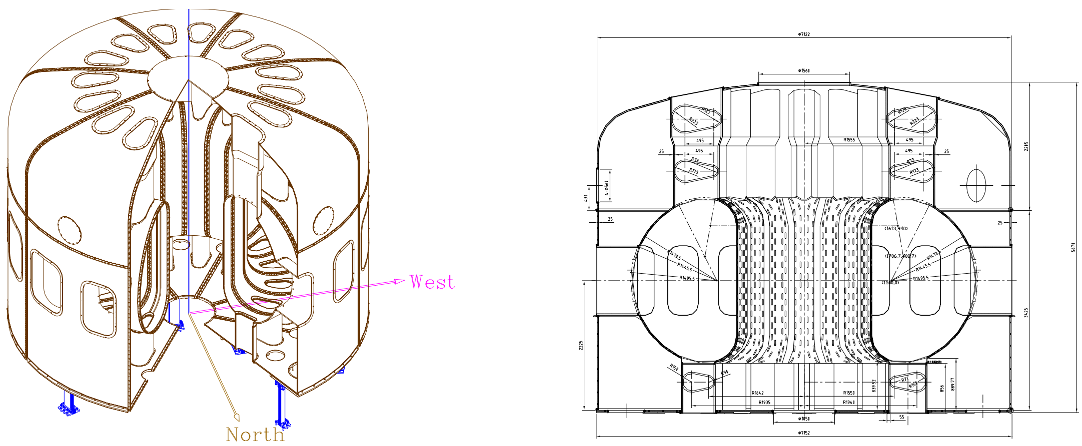


FIG.2.The Struture of Thermal Shields

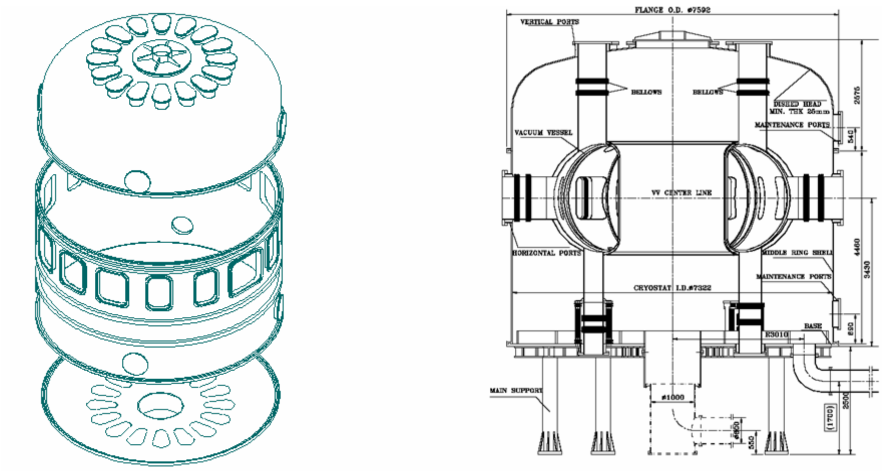


FIG.3.The Struture of Cryostat

on the base has been changed a lot for transferring the loads of the vacuum vessel and magnets to the base of the machine test hall directly. This modification is of great benefit to relief of stress inside of the structure. The base vacuum pressure of the cryostat shall be less than 1×10-5 Torr. All parts of cryostat withstand the design basic loads, which include external pressure atmost operating condition (1bar), dead weight and electromagnetic forces.

The cryostat has many penetrations, some as large as 1.7 meters diameter or 1270mm× 1130mm rectangle, providing various types of access from the outside to the tokamak. These include transport system cooling pipes, cryogenic feeds, auxiliary heating. Large welding bellows are used between the cryostat and the tokamak to accommodate differential thermal expansion and fabrication tolerances of the structure. Totally sixteen horizontal ports and thirty-two vertical ports were designed for the requirement of diagnostics and operation. In addition, there are eight horizontal man ports for future maintenance. There are 16 vertical access ports and four maintenance ports (the same four ports in the down section of middle ring) in lid wall. There are sixteen horizontal ports to the machine vacuum vessel at the machine equator. There are two types of sixteen vertical ports, eight cryogenic ports and a helium exhaust port on the base plate.The cryostat is made of 304L stainless steel. The cryostat is Φ7592mm outside diameter and 7095mm height (not including main support). The inside wall radius is 3661mm and the height of cylindrical section in middle ring is 4460mm. The lid is made of 28mm 304L stainless steel, in which the minimum thickness is 25mm. The non-standard dished head spherical and knuckle radii are 10000mm and 850mm, respectively. This type of head is lighter than the flat head of the early cryostat design and confirms to the machine shape. This arrangement also provides maximum buckling stiffness with minimum mass, and reduces the thickness of structural welds required. The thickness of cylindrical section is 25mm, with vertical and horizontal ribs between ports on the outside surface. The base is 60mm thickness stiffened plate bolted to main support. The inside surface facing vacuum has eight vacuum vessel supports and sixteen TF&PF supports. The cryostat mass is 78 tons including ribs, flanges, reinforcement. Its internal surface area and volume are $223m^2$ and $281m^3$ respectively.

3. Structure analysis for the vacuum vessel, thermal shield and Cryostat[4,5]

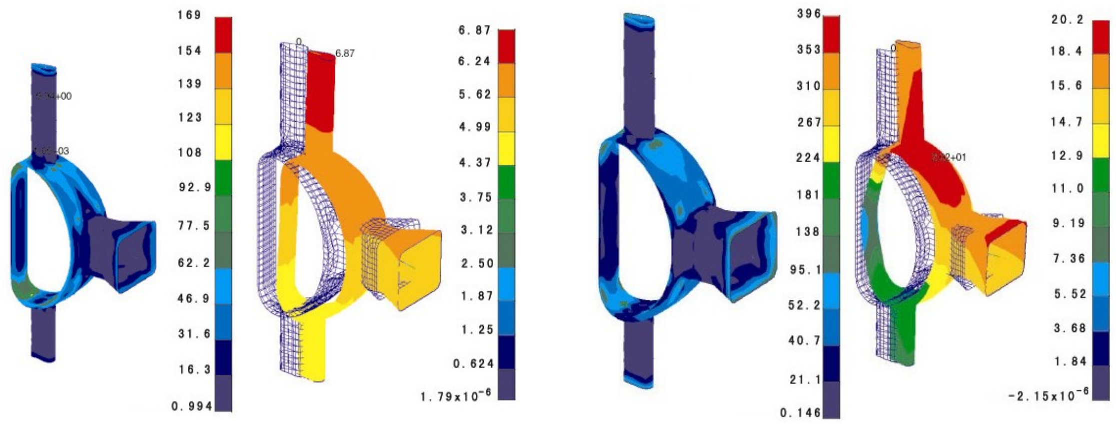
The vessel is double wall, several different working conditions must be considered. During vacuum test space between double wall will be pumped into vacuum, during plasma operation space between double walls will be filled with shielding water, and during bake out hot nitrogen will flow through the interlayer. Being superconducting tokamak when the device in operation both inside and outside of the vessel will be pumped into vacuum. While plasma breakdown and disruption electromagnetic forces is much strong. The vacuum vessel must withstand these individual and combined loading conditions during vacuum test, normal and off-normal operation. Considering symmetrical configuration of vacuum vessel, a model of 1/16 vacuum vessel is used for structure analyses. The cyclic symmetric conditions were applied to the toroidal edges of the sector. All of the ports have permitted to move slightly along the vertical or horizontal direction for the bellows installed on the port necks. The bottoms of supports under the vacuum vessel all can move and deform along the radical direction in a little bit. Bellows on ports and low stiffness supports are considered as spring element. At each end of ports in X (radial), Y (vertical), Z (toroidal) directions proper rigidity is applied on the analysis model. Rotate freedom degrees of each port end are not confined.

The two kinds of critical cases results were given, one is the plasma disruption during plasma operation (100℃ hot wall) and the other is the 250°C baking for vacuum vessel.

Case1 (plasma disruption with thermal and pressure load due to normal operation): The analysis has shown that the maximum stress intensity of 169Mpa including the thermal stress is appeared near the connecting area between up-vertical port and outer shell. The maximum displacement is 6.87 mm appeared in the top of the up-vertical port. The distribution of the stress intensity and deformation of the vessel is shown in Fig.4.

Case2 (250℃ baking for vacuum vessel):Due to the baking of 250℃ prior to the plasma operation thermal expansion of the vacuum vessel produces some deformation. Since the bottom of the vessel support structure is constrained in vertical direction, stress concentration occurred in a small area. Fig.4 shows the distribution of thermal stress and the deformation of the vessel due to 250℃ baking. The maximum stress is 396 MPa and maximum displacement is 20.2 mm. The maximum stress is mainly appearing in the connecting area between the down-vertical port and shell.

The main loads on the thermal shield are electromagnetic load, gravity load and thermal load. Eddy currents induced in the thermal shields during plasma disruption will produce electromagnetic (EM) loads. Electrical breaks in the toroidal direction for the thermal shield, is required to mitigate these loads. Detailed finite element static EM analyses and stress analysis have been performed. The Max. displacement is 5.12 mm and the Stress is less than 300MPa indicate that 16 toroidal breaks are sufficient from the standpoint of limiting stresses and deflections to acceptable values.Fig.5 have given their distribution.



Case1 Case2

a.Stress (MPa) b.Deformation(mm) a.Stress (MPa) b.Deformation(mm)

FIG.4. Maximum stress and deformation of the vessel

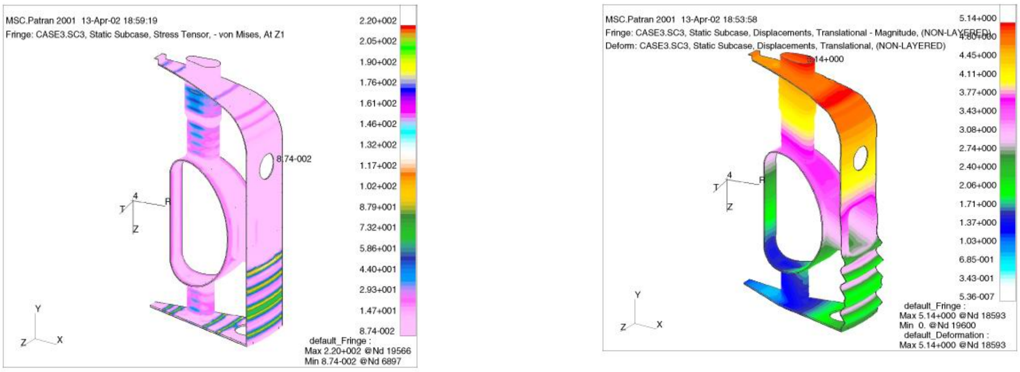


FIG.5.Thermal Stress Analysis for Thermal Shields

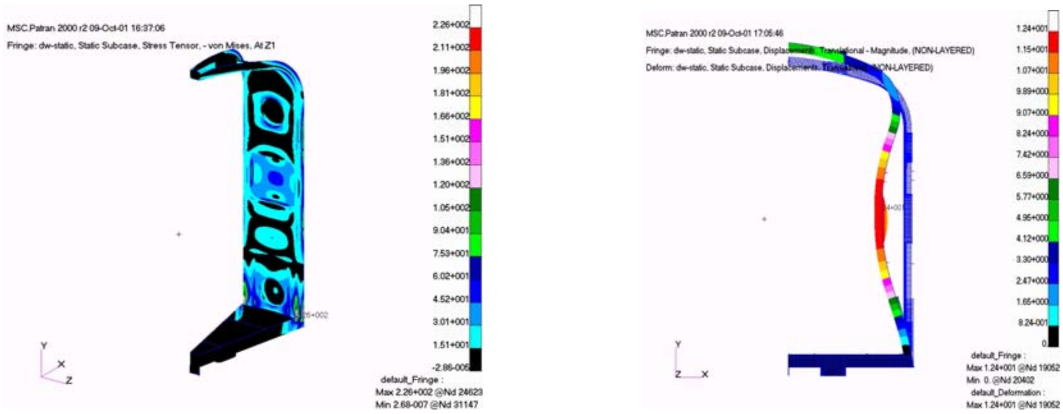


FIG.6. Stress Analysis for Cryostat

Based on the cryostat geometry dimension and symmetry, a 1/16 segment was chosen as the finite element model. The cryostat model included main flanges, ports, reinforced vertical and horizontal ribs. It has 17300 nodes and 17301 quadrangle shell elements. The material property (304L) applied in the analysis. The cryostat must take 0.1MPa external loading (vacuum pressure), electromagnetic loads caused by eddy currents and dead weight. The boundary condition is that the sector edge in toroidal direction is clamped and not allowed to move toroidally. The top central end of the section along the vertical port direction is not permitted to move. The bottom surfaces of the base under the cryostat are fixed. Fig.6 have shown the stress intensity and displacement distribution.

4.Fabrication of vacuum vessel, thermal shield and Cryostat

The vacuum vessel consists of 16 segments. It is not a 16-sides polygon; the surface of the vacuum vessel is a torus with “D” shape cross section. During fabrication each segment will be made separately. Along the poloidal direction inner shell and outer shell split into 4 pieces. Each piece is press formed to obtain the required shape at room temperature. It is difficult to control spring back of the plates at room temperature. In order to obtain acceptable precision of the shape some special technology was developed. When the shell pieces and ribs are assembled, a special technical facility was used. On the facility first of all to weld inner shell pieces together to obtain “D” shaped ring, then weld ribs to inner shell, then weld outer shell pieces to ribs and weld the outer shell pieces together. After completed these welds machine holes for ports and weld port connections in the holes. During weld the parts together the special technical facility can control the vessel section distortion, and vibration aging is used for each segment after welds to reduce residual stress. Fig.7 shows the vacuum vessel section

FIG.7. Fabrication of Vacuum Vessel

without ports. The dimension error of this section is around 2 mm. The ports, flanges and supports are made separately. After all parts of the device are assembled together then the ports with flanges weld to ports' connections [6].

The prototype of 1/16 VVTS, up-vertical, bottom-vertical and horizontal VPTS and CTS bottom platform have been fabricated in Wuhu boiler factory to check the manufacture feasibility. The most difficult parties are the sector of VVTS and the top cap due to their three- dimensional curve face; the bottom platform due to its very thin panel, weak structure, big area and relative high accuracy requirement. Therefore, a lot of die and technological tooling for forming and welding was designed and prepared. The cooling pipes were bend into a two dimensional curve according to the cooling channel design at first and then formed to three-dimensional curve face in a die under the press. The thin panel was deformed using same way and then the two panels were welded on the cooling pipe using a welding tool. The Fig.7 shows the technology process of VVTS, bottom platform of CTS as well as the up vertical, bottom vertical and horizontal VPTS. The deformation after welding is considerable big, especially the CTS bottom platform has considerable dimension deflection and has to be reinforced. The engineering design has been finished and the fabrication started and completed in 2002 and 2004 respectively. Two halves of cylinder rings for the fabrication of the cylindrical section are precisely bent to the required shape and carefully welded together to form the central cylinder section. Precious cutting of the holes for ports was performed by numerical control (NC) boring and milling machine tool after the previously rough cutting using plasma jet technique. During the fabrication, the vibration stress relief (VSR) method was used to relief the residual stress formed by welding process. Vacuum tightness of the welds was checked by an integral helium leak test of each whole section. The contours of the sections were measured by optical measuring system and met well the given tolerances. The paper will summarize the structural analyses, the design activities and give a short description of the fabrication of the cryostat component.

FIG.8. Fabrication of Thermal shields


FIG.9. Fabrication of Cryostat

5.Testing results of vacuum vessel, thermal shield and Cryostat

The first commissioning started from Feb.1 and finished on March 30 and be success in the first plasma operation in the end of Sep.2006 at the Institute of Plasma Physics, Hefei, Anhui, China. It consists of leakage testing at room temperature and low temperature, pumping down, cooling down all coils, current leads, bus bar and the thermal shielding, exciting all the coils, magnetic configuration measurement and magnets warm up. The electromagnetic、thermal hydraulic and mechanical performance of EAST TF and PF magnets have been tested. All sub-systems, which include pumping system, cryogenic system, PF& TF power supply systems, magnet instrumentation, quench detection and protection, water cooling, data acquisition, main control system, plasma control system (PCS), interlock and safety system, have been successfully tested. Pumping system started on Feb.7 and successfully operated through whole commissioning experiments. The highest vacuum in cryostat reached $3.8x10^{-5}$Pa that is above the operation requirement of $2x10^{-4}$Pa. And the vacuum vessel has reached 1.6 $x10^{-5}$Pa after baking. The thermal shields were cooled down to 80-100 K by helium gas from the refrigerator. The heat load of the CTS is 5.5 kW and the heat load of the VVTS and VPTS is 4.2 kW, and the surface emissive coefficient is round 0.1 according to the result.

6.Summary

EAST has been successfully constructed and start operation in this month. Baesd on the calculation and engineering test the present structure design of vacuum vessel, thermal shields and cryostat is succeful and safety. According to the allowable stress criteria of ASME, the maximum integrated stress intensity on these key components is less than the allowable design stress intensity $3S_m$.The highest vacuum has been reached $3.8x10^{-5}$Pa in cryostat and 1.6 $x10^{-5}$Pa in vacuum vessel,which is above the plasma operation requirement. The thermal shields were cooled down to 80 –100 K by helium gas from the refrigerator. The heat load of the CTS is 5.5 kW and the heat load of the VVTS and VPTS is 4.2 kW, and the surface emissive coefficient is round 0.1 according to the result.All of these have given EAST engineering team the further confidence to make sure that EAST will provide fusion community a very good international research facility for steady state divertor plasma research.

[1] Y.X.Wan, J.G.Li,P.D.Weng, First engineering commissioning of EAST, Plasma science and technology,2006, 8 (3): 253-254

[2] Design of EAST, ASIPP Report, Institute of Plasma Physics, Chinese Academy of Sciences , Oct. 2003.

[3] S.T.Wu W.Y.Wu Y.T.Song et al., Design of the HT-7U Tokamk Device, 18^{th} IEEE/NPSS Symposium Fusion Engineering, Albuquerque, New Mexico, Oct.25-29, 1999: 549-552,

[4]R.S.Granetz,I.H hutchinson,J.Sorci et.al, Disruptions and Halo current in Alcator C-MOD, Nuclear fusion, 1996, 36(5):545-556

[5]Y.T. Song, D.M. Yao,S.T. Wu, et al. Static and Dynamic mechanical analysis for the vacuum vessel of EAST superconducting tokamak device, Plasma science and technology 2006,8(2): 221-228

[6] Y.T. Song, D.M. Yao,S.T. Wu, et al. A Lower Rigid Support System for HT-7U, Plasma Science and Technology, 2002,4(3): 1289-1296