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Engineering Design of KSTAR Tokamak Main Structure

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Abstract. The main components of the KSTAR (Korea Superconducting Tokamak Advanced Research) tokamak including vacuum vessel, plasma facing components, cryostat, thermal shield and magnet supporting structure are in the final stage of engineering design. Hyundai Heavy Industries (HHI) has been involved in the engineering design of these components. The current configuration and the final engineering design results for the KSTAR main structure are presented.

1. Introduction

The main components of the KSTAR tokamak structure are the vacuum vessel (VV), plasma facing components (PFCs), cryostat, thermal shield (TS) and magnet with its supporting structure as appeared in FIG. 1. Now they are in the final stage of engineering design. HHI has been involved in the engineering design of the PFCs, VV, cryostat, magnet supporting structure and their interfacing supporting structures. The overall configuration and the detailed dimensions of the KSTAR structure have been determined. The installation and fabrication-related documents covering fabrication procedure, surface preparation and cleaning, inspections, installation procedure, etc., have also been prepared. Here the current configuration of the KSTAR structure except for the superconducting magnet is described briefly and then the design methodology and the analysis results are presented.

2. Plasma Facing Components

The PFCs consist of the divertor, inboard limiter, passive stabilizer (including ripple armor), neutral beam shinethrough armor, and poloidal limiter as shown in FIG. 2. Each has bolted graphite or carbon-fiber-composite (CFC) tiles supported by SA240-316LN (for the divertor,

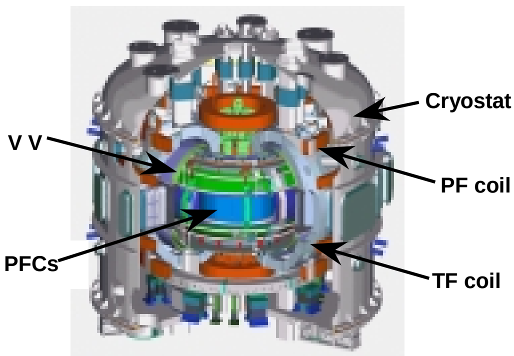

FIG. 1. KSTAR tokamak structure

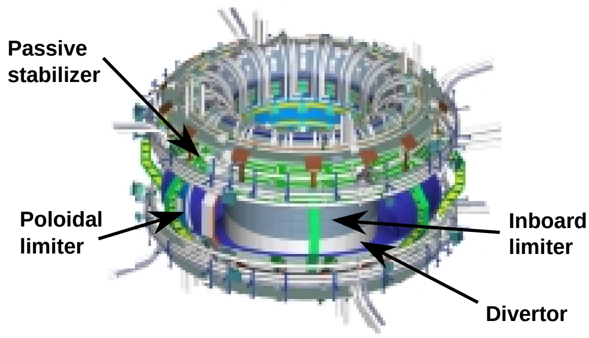

FIG. 2. KSTAR plasma facing components

inboard limiter, neutral beam shinethrough armor, and poloidal limiter) and CuCrZrMg (for passive stabilizer) backplates. The backplates are attached to the VV through the PFC supports except for the poloidal limiter which resides on the mechanical support of passive stabilizer. Basically the PFCs are designed for the baseline operation, however, inboard limiter and passive stabilizer can accommodate upgrade operation conditions. The backplates of divertor, inboard limiter and passive stabilizer are divided into 16 sectors of 22.5 degree each by considering the coolant/baking gas pipe size, assembly and maintenance. Each sector has its own separate cooling channel and will be connected with neighboring sectors by bolts.

All baseline PFCs will be water-cooled during plasma operation to maintain the surface temperatures of graphite and CFC tiles to be less than 600℃ and 1200℃, respectively. The baking temperature of the PFCs, 350℃, can be achieved within 24 hours and their operation scenario has been established [1]. Coolant and baking gas requirements on operation and bakeout have been obtained and the baking/cooling channel design has been carried out. Baking gas for the PFCs is supplied by a separate route from the VV. Stress analyses for the situations of plasma disruption, coolant pressure and bakeout have been carried out using ANSYS code [2]. The contribution of EM loads to the design was much less than the thermal loads generated during bakeout. Thermal analyses on the carbon tiles have also been performed to determine the required thermo-mechanical properties and to select the proper materials. Cryopump of over 50 Torr·l/s at 1 mTorr will be installed in the divertor pumping plenum. The cryo-surface temperature of less than 4.3 K is maintained with 3.7 K two-phase liquid helium and regeneration will be done within 10 minutes for 20 seconds of baseline operation.

3. Vacuum Vessel

The VV consists of the inner and outer shells, horizontal, vertical and slanted ports, and the leaf spring style vessel supports with various types of bellows as appeared in FIG. 3. Double walls are separated by poloidal and toroidal ribs and filled with shielding water. The overall external dimensions of the main body are 3.39 m high, 1.11 m inner radius and 2.99 m outer radius. The VV material is SA240-316LN. The VV was designed to be capable of achieving the base pressure of 1×10^{-8} Torr, and also to be structurally capable of sustaining the vacuum pressure plus baking gas pressure between shells, and the electromagnetic (EM) and thermal loads during plasma disruption and bakeout, respectively.

The VV will be baked out to at least 250 ºC at the inner wall by hot nitrogen gas flowing through the channels formed between double walls and the reinforcing poloidal ribs, and these temperatures will be reached within 24 hours. The 3-D temperature distribution and the resulting thermal loads in the vessel during bakeout were calculated. The maximum EM loads on the VV and PFCs induced by eddy and halo currents resulting from the plasma radial and vertical disruption scenarios have been estimated using the SPARK code [3]. The EM loads on the PFCs are important to the design of the PFC support and its interface area to the VV. The disruption events consist of 1 ms of thermal quench and 4 ms of current quench. Total poloidal halo currents are assumed to be 40 % of plasma currents and have toroidal non-symmetry with a peaking factor of 2:1 [4]. The extensive stress analyses have been performed on the vacuum vessel, cryostat, and magnet supporting structure under various load conditions including static (dead weight, coolant and vacuum pressure), thermal (baking gas and cool down temperature), dynamic (EM and seismic forces) and their combined loads using the ANSYS code. The values of the loads and maximum stresses for each component are summarized in Table I. Allowable stress limits are from ASME design code[5]. The thermal

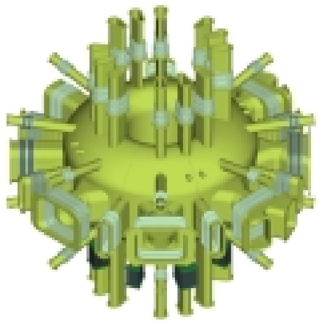

FIG. 3. KSTAR vacuum vessel

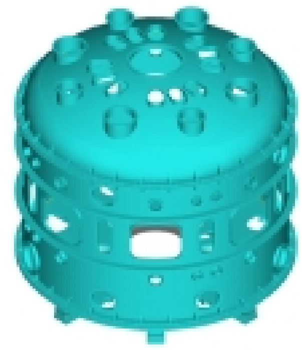

FIG. 4. KSTAR cryostat

load produced the high stresses and displacement for the vacuum vessel, and played a major role in designing the vacuum vessel. The stress analysis for the seismic load condition has been done, too. All resulting stresses were below the allowable stress limit for all components and it has been found that the VV and its supports are structurally rigid. To examine fabricability, a prototype of vacuum vessel is being constructed, measured and inspected. The fabrication and installation-related documents are also prepared.

TAB. I: STRUCTURAL ANALYSIS RESULTS OF THE KSTAR TOKAMAK

Structure	Load Conditions		Load	Stress Analysis Results		
				Max. Stress (MPa)	Allowable Stress (MPa)	Max. Displacement (mm)
Vacuum Vessel	Dead Weight (DW)		100 ton	34.8	173	0.3
	Coolant Pressure (CP)		4 bar	136.5	173	1.11
	Vacuum Pressure (VP)		1 bar	112.6	173	5.34
	Thermal Load (TL)		250℃	206.5	347	21.9
	Seismic Load (SL)		H=0.12g, V=0.08g	23.0	207	1.10
	EM Load	Eddy Radial	6 ton	31.9	173	0.32
		Halo Radial	49 ton	119.1	173	5.40
		Eddy Vertical	330 ton	117.7	173	0.90
		Halo Vertical	151 ton	139.2	173	1.89
	Combined Loads	DW+CP+VP+EM		142.9	173	3.00
		DW+CP+VP+EM		151.5	173	3.94
		DW+CP+VP+TL		242.7	347	22.5
Cryostat	DW		600 ton	40.65	173	0.65
	DW + VP		600 ton +1 bar	149	173	4.2
	Port Analysis		Port DW +1 bar	65.33	173	2.44
	Support Analysis		600 ton	74.37	173	0.08
	Seismic Load(SL)		H=0.12g, V=0.08g	11.07	207	0.47
Magnet Support Structure	DW+EM-F		343 ton +230 ton	102.5	206	0.73
	DW+EM-F+TL		343ton +230ton +4.5K	276.4	413	11.59
	DW+EM-F+TL+SL		343ton +230ton +SL	279.2	496	11.59
	Seismic Analysis		H=0.12g, V=0.08g	145.6	247	1.95

4. Cryostat

The cryostat shown in FIG. 4 is an 8.8 m diameter, single-walled cylindrical vacuum vessel with a dome-shaped lid that provides the vacuum boundary to protect the magnet. Electrical and mechanical penetrations with bellows have been designed to restrict the displacements of all of the ports due to EM loads and thermal loads within the allowable limits. The cryostat design has been executed to satisfy the performance and operation requirements such as a base pressure of $1x10^{-5}$ Torr. The cryostat vessel has also been designed to be structurally capable of sustaining the atmospheric pressure plus a dead weight of the VV, PFCs and magnet and the dynamic EM loads under all plasma disruptions by performing modal, buckling and stress analyses. The maximum stress of 149MPa for the cryostat occurred under the dead weight and vacuum pressure load conditions as shown in Table I.

5. Thermal Shield

The purpose of the thermal shield (TS) is to reduce the thermal radiation from the room temperature side to the coil temperature (4.5K) region. There are two types of thermal shields; one is the vacuum vessel thermal shield (VVTS) located 4 cm off the VV outer wall and the other is the cryostat thermal shield (CTS) located 15 cm off the inside cryostat. Both shields act as heat barriers between superconducting magnets that operate at 4.5 K and the surfaces of cryostat and VV whose temperature is 300 K. The TS is composed of multilayer insulation (MLI), cryopanels, and supports. Aluminized Kapton and aluminized Mylar are used as MLI materials for the VVTS and the CTS, respectively. Also CFRP (Carbon-Fiber Reinforced Plastics) and GFRP (Glass-Fiber Reinforced Plastics) are selected as VVTS and CTS support materials, respectively. The cryopanel was designed to maintain a maximum temperature of 80 K during normal operation and 100 K during bakout, respectively. The TS coolant is gaseous helium operating at 20 bar and its inlet and outlet temperatures are 60 K and 80 K, respectively, during normal operation. The thermal loads on the cryopanel are summarized in Table II.

TAB. II: THERMAL LOADS ON THE CRYOPANEL.

Structure	Normal Operation [kW]	Hard Baking [kW]	Soft Baking [kW]
Cryostat	2.5	0	2.5
Vacuum vessel	2.7	15	10.3
Sum	5.2	15	12.8

6. Magnet Supporting Structure

The magnet supporting structure consists of one supporting ring, eight supporting posts, and eight vertical limiters as shown in FIG. 5. The supporting ring cooled by 4.5 K supercritical helium is a rigid ring structure with a rectangular cross section. The supporting post, which has an 80 K active cooling module on the thermal anchor block, is not only a flexible structure that absorbs thermal shrinking of the superconducting magnet but is also a rigid structure that supports the magnet weight of about 300 tons and the plasma disruption loads of about 200 tons. Each supporting post is bolted to both the supporting ring and the base structure of the cryostat and has a temperature distribution of 4.5-300 K. CFRP is used for the supporting post material to reduce coolant heat loss from the magnet to the cryostat and to assure structural rigidity. The magnet vertical limiter is a vertical displacement limiter of the

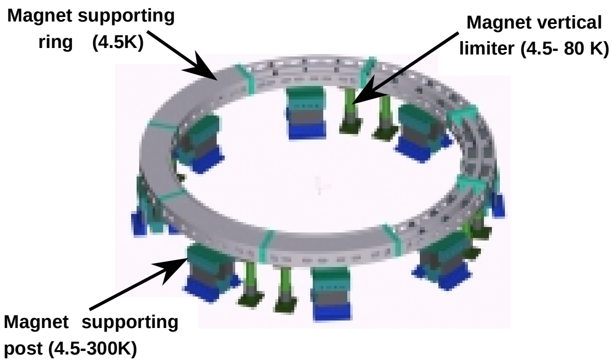

FIG. 5. KSTAR superconducting magnet supporting structure

FIG. 6. Prototype of the magnet supporting post

supporting ring to protect the supporting post. Structural analyses for the supporting structure under design loads has been performed to verify its structural reliability and the results are summarized in Table I.

A real size prototype of the supporting post shown in FIG. 6 was manufactured to verify the structural safety and fabricability. Static and compressive cyclic load tests equivalent to the magnet dead weight and the 320 ton of maximum plasma vertical disruption load, respectively, have been performed at liquid-nitrogen temperature. No failure occurred and it was found that all stresses are much smaller than the allowable limits.

7. Conclusion

The engineering design on main components of the KSTAR tokamak structures has been carried out. The extensive thermal and structural analyses on PFCs, the vacuum vessel, the cryostat, the thermal shield, and the magnet supporting structure have been done so far. The detailed drawings for these structures have been produced. The fabrication and installation-related documents are also prepared. To examine fabricability, a prototype of the vacuum vessel is being constructed, measured and inspected. Also, the structural safety and fabricability of the supporting post has been verified successfully through the test of a real size prototype.

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References

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