Recent Progress of GIS/GDC Design and Manufacturing for ITER

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ABSTRACT： The recent progress of the GIS and GDC is introduced. The detailed design of GDC electrode has been finished and the progress for some key techniques has been obtained; the critical components in GDC electrode have been developed and tested; the transient flow behavior for each gas have been analyzed and the preliminary study of magnetic shield has been done; a basic structure design of GVB is presented; a prototype of GDC electrode is to be manufactured and the test scheme has been drafted; the tritium compatibility and safety design review of GIS and experimental study on transient flow behavior are expected to be carried out in the near future.

Key Words: gas puffing, ITER, wall conditioning

1. Introduction

The main purpose of the wall conditioning system in tokamak device is to control the oxygen and other impurities from the plasma facing wall. In ITER device, several methods are proposed to be used. They are Baking, Glow Discharge Cleaning (GDC), Electron Cyclotron Resonance discharge cleaning (ECRH-DC), ion cyclotron resonance discharge cleaning (ICRH - DC). ITER GDC system mainly includes the GDC electrode, Power Supply, control system and associated peripherals.

The gas injection system (GIS) is designed to provide normal fuelling to plasma and wall conditioning, which mainly consists of the gas introduction line, Gas valve boxes (GVB), gas supply manifold, control system and associated peripherals. GIS shall provide the following functions: fuelling with specified flow rate and response time, and injecting impurity gases for emergency fusion power shutdown and radiative cooling of divertor respectively, as well as the service of gas supply for the pellet injection system, neutral beam system and wall conditioning.

The design of GIS/GDC system faces many challenges and difficulties in techniques. The tritium compatibility and safety design, the magnetic shield design for the GVB, the structure design of GVB and gas supply manifold still need to be studied. And the key components of GDC electrode also face many challenges, such as, electrical insulation, cooling loop design and corresponding fabrication process for its inner structure. In addition, the GIS/GDC control system conforms to the CODAC guideline is still open.

Chinese Participation Team (CN PT) is responsible for the procurement package of GIS and GDC system. From 2005, Southwestern Institute of Physics (SWIP) started the research of ITER GIS/GDC system. Till now, the conceptual design of GIS/GDC system has been reviewed based on Design Description Document (DDD) of Fuelling and Wall Conditioning System[1-3] and some preliminary results of calculations and simulations have been obtained.

2. Glow Discharge Conditioning System

According to the requirements, the current density on the first wall surface shall be higher than 0.1A/m^2 during GDC. In order to get a uniform current density distribution, six electrodes are placed roughly equally-spaced around the device toroidally and each GDC electrode shares one port and transportation mechanism with one In-Vessel Viewing System(IVVS). GDC electrode shall mainly be in one of three states: 1) the electrodes transported into the vacuum vessel by the transporter work as discharge electrode during GDC conditioning operation; 2) the electrodes behind the Vacuum Vessel (VV) triangular support work as neutron shielding plugs and first wall during plasma operation; 3) the electrodes park to a specific position to give space for other operations. In the present design, water of 240 ^{o}C/4.4 MPa or 100 ^{o}C/ 4.2 MPa at inlet flows into the GDC electrode from the divertor cooling system during baking and plasma discharge, respectively.

The challenges of GDC system include the operation safety of deployment, insulator under high pressure and high temperature, and compatibility with the working condition during plasma operation such as neutron irradiation and magnetic field. In the following, the relevant R&D of GDC electrode will be introduced

2.1 Electrode structure design

At present, the preliminary design of GDC electrode has been completed. The structure, shown in Fig.1, consists of four major parts, namely electrode head, central conductor, tail rod and electrode housing. It's designed that the edges of CuCrZr alloy electrode head to be rounded and their surfaces to be polished in order to prevent arcing. A special-shape structure is designed for the tip of electrode head to reduce the deformation and stress imposed on the welding position of the copper/ beryllium (Be/Cu) Hot Isotonic Pressure (HIP) as low as possible. The central conductor, which is used to supply current to the electrode head, has two parts. The inner one extends from the end of tail rod to the tip of electrode head and close assembled in the 316 L-IG stainless steel outer shell. An axial hole in the CuCrZr inner conductor is used

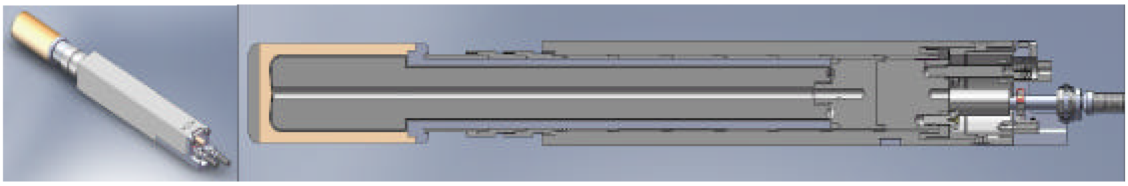


Fig.1 3D model of GDC electrode (left), the section plane of GDC electrode(right)

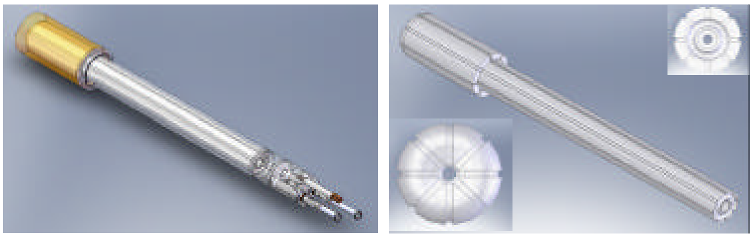


Fig.2 the structure of water flow path inside GDC electrode to route the cooling water from the end of tail rod to the electrode tip and six channels milled directly on the outside wall of the inner conductor to provide a return flow path (shown in Fig.2). The outer shell is welded with electrode head by electron-beam welding. The tail rod forms the electric connection and water pipe interface to the electrode. A knife-edge type thread seal together with gas tungsten arc welding (GTAW) are selected to seal the water inlet and outlet between the tail rod and the center conductor (seen in Fig3). A ceramic-metal sealing insulator is used to isolate electrically the water hoses and electrode. To lessen the impact of the inlet high water pressure on ceramic insulator, a special bellow is adopted at the rear of tail rod. The stainless steel electrode housing is hollow with quadrate shape outside. The central conduct is located inside and fixed by special design. Considering thermal expansion of materials, three shapes of ceramic insulator with cascade structure have been elaborately designed and placed in space between the center conductor and electrode housing to provide the electric isolation. This cascade structure design could effectively prevent deteriorating of the isolation performance, arcing and breakdown which may be caused by the re-deposition on the surface of insulator during glowing discharge conditioning. All the insulator adopt the hot pressed ceramic (99.5% Al_2O_3) based on the isolation voltage, irradiation resistant and the manufacture process consideration. Till now, some key components have been produced and experimental tests have been done. The next work is to continue the analysis of mechanics, thermodynamics and hydrokinetics to optimize the design and increase the reliability and lifetime of the electrode.

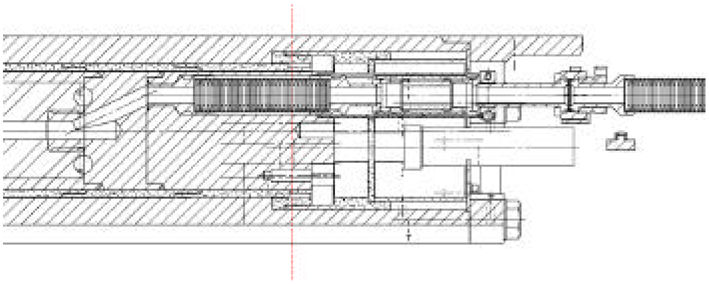


Fig.3 Section plane of the tail rod

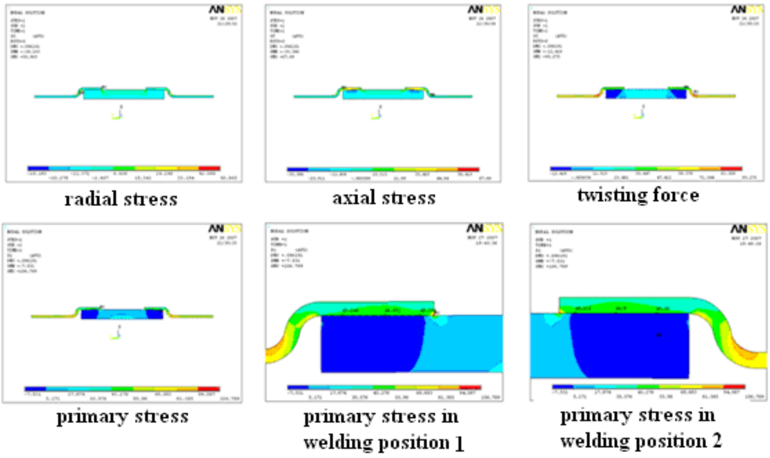
2.2 Study and experimental test of key component

Water leaking is a serious potential risk in GDC electrode. As the intrinsic material performance of ceramic, the reliability of ceramic-metal sealing insulator is a challenge under high neutron radiation environment and cooling water with high pressure and high temperature. The stress analysis, experiments and the ceramic-metal vacuum welding procedure by using pure copper have been done.

Table 1 Tensile performance data

Material	E loss of flexibility(GPa)	Poisson's ratio ν	σ_b Ultimate Strength(MPa)	α Linear expansion coefficient (10^{-6} °C $^{-1}$)
4J31	139	0.3	539	6.3
99% Al_2O_3	350	0.3	240	7.8

The stress analysis has been carried out by using the finite element analysis. The relevant parameters of 4J31 Kovar alloy and 99.5% Al_2O_3 ceramic material are listed in the table1. The load boundary is set as the average pressure of 6.6MPa on the inner wall of the component and the temperature is considered to be constant at 240°C. Based on these assumptions, the stress intensity of the component has been analyzed and the results are shown in Fig.4. The maximum stress intensities for the Kovar and ceramic are 107 MPa and 65 MPa, corresponding to the safety factors of 5.04 and 3.69 respectively. The analysis also shows the maximum breakage stress for this component is 16MPa, which meets the technical requirements for GDC cooling loop.


radial stress axial stress twisting force

primary stress primary stress in welding position 1 primary stress in welding position 2

Fig. 4 Stress analysis of the ceramics-metal sealing component

The ceramic-metal vacuum welding procedure by using 100% copper TU1 as solder has been studied and the sample of this ceramic-metal sealing insulator has been developed. For the performance comparison, some other samples have been developed by using 95% Al_2O_3 ceramic instead of 99.5% Al_2O_3 ceramic with AgCu solder and pure copper solder. Leakage rate of less than 1×10^{-11}Pa•m^3/s has been achieved for all of the samples before the following tests.

Thermal shock test: liquid nitrogen shock and heat shock have been adopted to test nine samples (three per type). In liquid nitrogen shock test, the samples are dropped into the liquid nitrogen and kept for two minutes, then picked out to the air until it reaches room temperature. Repeat the process for ten times, and then do the leak detection by using helium mass spectrometer. In heat shock test, the samples are put into the oven and heated to 270 °C, then taken out to cool down to room temperature naturally. Repeat the process for ten times, and then do the leak detection. The test results show that the leakage of all the samples are less than 1×10^{-11}Pa•m^3/s.

Hydraulic pressure test: nine samples (three per type) are selected. The sample with one end closed is connected to the water press directly, and three test pressures of 4.4MPa, 6.6MPa and 10MPa have been set for the testing. Each test lasts five minutes, after that, the sample is demounted and checked the leak tightness. The result shows that all the samples meet the requirement of leakage rate of less than 1×10^{-11}Pa•m^3/s.

Tensile test: nine samples (three per type) are selected. The sample is welded with one drawbar on each side firstly, and a port for leak detection is designed in one side. Then the sample is lathed to make sure the coaxiality of these two drawbar. After that, the sample is mounted on the special test bed and two tensile testing loads of 1100N and 1550N are set and kept for one minute. After each load testing, the sample is demounted and the leak rate is measured. The data show the leakage tightness of all the samples keeps constant. Finally, the sample in each type is selected for the breakage test. The maximum loadings for the sample of 99.5% ceramic welded to Kovar with copper, 95% ceramic welded to Kovar with AgCu and copper are 18 KN, 10KN and 16.5KN accordingly. And all the breakpoints are in the ceramic body, which proves the rationality and reliability of the ceramic-metal welding process.

Insulation test: a sample in each type is selected and put into a vacuum chamber. One end is connected to the anode of high-voltage power supply; the other is connected to the cathode and the wall of vacuum chamber. When the vacuum pressure in the chamber reaches 10^{-4} Pa, high purity Ar gas is injected into the chamber according to the test requirements step by step. Then the change of the voltage and current is monitored with the output scanning of power supply. It is found that no breakdown happens in 10^{-4} Pa even the voltage of power supply increase to 6,000V. When the vacuum pressure increases to 2×10^{-1}Pa, the breakdown happens at 3,500V. After that, the breakdown voltage increases with the vacuum pressure, no breakdown happens at 4,000V in 3Pa. This test demonstrates that the ceramic-metal sealing insulator meets the insulation requirement of GDC electrode.

The above tests prove that the design of ceramic-metal welding components could meet the current requirements of GDC electrode. But there could be additional loadings impacting on the ceramic components because of the relative movement between the two parts of the central conductor. So the further study of its performance and the protection design shall be carried on for safe operation. Now, these jobs are just initiated.

3. Gas Injection System（GIS）

According to the function and design description, the gases of H_2, D_2, DT, T_2 ^{3}He and ^{4}He have to be injected uniformly from the top of the vessel in order to minimize erosion of the first wall by charge exchange neutrals and localized heating around the injection points. And the impurity gases of Ne, N_2 and Ar have to be injected into the divertor area simultaneously for alleviating the heat load on target plate by radiative cooling. The GIS response time (to 63%) is required to be less than 1 second for the case of 20 $\mathrm{Pa\cdot m^3/s}$ throughput for plasma fuelling and 5 $\mathrm{Pa\cdot m^3/s}$ throughput for radiative cooling[4]. The gas pressure supplied by tritium plant is expected to change from 0.12MPa to 0.09MPa based on the safe operation of tritium. The strength of peak poloidal magnetic field in vicinity of the GIS valve boxes is about 1500—2000 Gauss in the preliminary estimation [5].

3.1 Pressure drop calculation and transient flow analysis

In the former design, the pipe selection based on JIS G 3459 standard and the gas pressure in tritium plant is 0.12MPa. But now only the ASME or ISO standard pipe can be used because of the standardization requirement, so the ASME B36 Std-40 standard pipe is selected and the gas pressure in tritium plant is supposed to be 0.09MPa in this estimation. All the related parameters and the maximum pressure drop for each working gas in the gas supply manifold under the peak throughput are listed in the table 2. In this table, the maximum pressure drop either in Upper port or in Divertor port in this new estimation is two times larger than that in the former estimation.

Table 2. Maximum Pressure Drop in gas supply manifold

Gas species	Peak Throughput ($Pa\cdot m^3/s$)	JIS G 3459+ 0.12MPa			ASME B36 STD-40+ 0.09MPa		
		Inner Diameter (mm)	Max Pressure Drop (kPa)		Inner Diameter (mm)	Max Pressure Drop (kPa)	
			Upper Port	Divertor Port		Upper Port	Divertor Port
D_2	240	22.2	0.2	0.2	21	0.5	0.5
DT	240	22.2	0.3	0.3	21	0.6	0.6
H_2	240	22.2	0.1	0.1	21	0.3	0.3
N_2	100	13.3	3.0	2.9	12.7	6.2	6.0
He	120	13.3	1.0	1.0	12.7	2.0	2.0
Ne	100	13.3	2.7	2.6	12.7	5.6	5.5
Ar	100	13.3	4.2	4.0	12.7	8.6	8.4

The transient response characteristics have been analyzed for each working gas. Here, considering the maximum pressure losses in the gas manifold, the initial pressure of 0.08MPa is assumed as the boundary condition for the analysis. The simulation shows that the tube inner diameter is irrelevant with the response time if no “choked flow” appears. The transient flow behavior for various gases at a given throughput of 5 Pa·m3/s through a tube with 10.4mm in inner diameter and 20m in length have been simulated and the result is shown in Fig.5. It is clear that the fast response time for the hydrogen species is easy to achieve. But for the impurity gases, the response time for each GVB is much longer than that of hydrogen species, especially neon. Neon has the longest response time (≈1s) because its conductance is the lowest in these gases. The experimental study of transient flow behavior should be carried on to benchmark the modeling in the next phase. In order to meet requirement, a special technology of flow control for the impurity gas puffing needs to be developed, for example, mini-pulse or mixture control with hydrogen species.

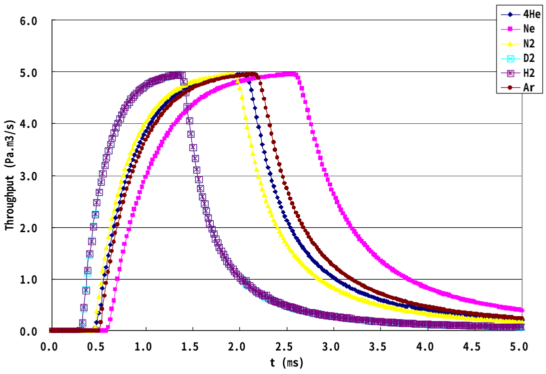


Fig.5 Response to various gases in the same throughput (Throughpu = 5Pa.m3/s, tube inner diameter = 10.4mm, and length = 20m)

3.2 Preliminary study of magnetic field design

In the conceptual design, the infinite cylinder model has been used to estimate the thickness of shielding material. But this model is not suitable because of the distribution variation of magnetic field and the space restrictions in vicinity of GVB. In order to evaluate the effect of the direction of external magnetic field on the shielding performance, a simple model has been created and three vector directions of external static magnetic field (perpendicular, parallel and oblique) have been imposed on the cylinder box. The dimension of the shield is Φ94cm×98cm. The external magnetic field is supposed to be 1000 Gauss and the thickness of the Co-Fe alloy shielding is 2cm. The simulation results in these three cases are shown in Fig.6. It shows that the performance of this magnetic shield becomes worse when the external magnetic field is oblique to the cylinder, and the magnetic field inside the cylinder has different distribution in each case. In the next step, further design of magnetic shield should be carried on, the penetration and the layout of element inside GVB will be taken into account.

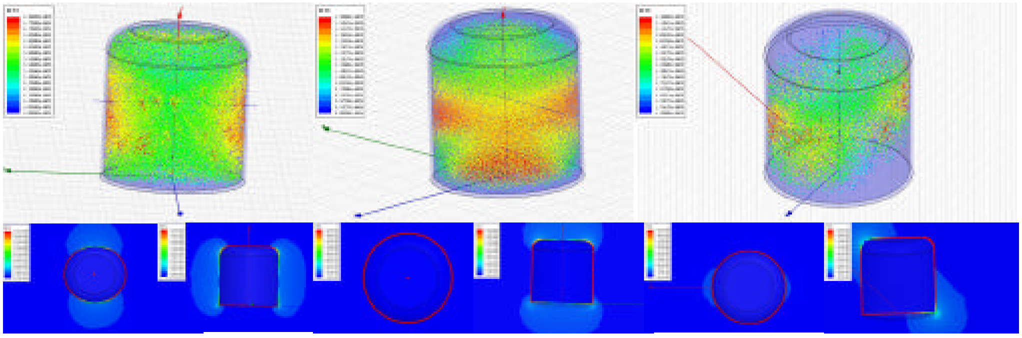


Fig.6 the distribution of magnetic field in shielding material and inside the cylinder. Left: Magnetic field is perpendicular to the cylinder, Middle: Magnetic field is parallel to the cylinder, Right: Magnetic field is oblique to the cylinder at the angle of 45°.

3.3 Basically Structure of GIS Valve Box

The GIS design from the manufacturing point of view has been carrying on. VAT 57 serials all-metal angle valves are selected as a candidate isolation valve in GIS, which could provide high conductance, high radiation resistant, low leak rate and tritium compatibility. The MKS Baratron Capacitance Manometer 627B serials are chosen as a candidate for pressure measurement, which could provide high accuracy, tritium compatibility and low sensitivity to the stray magnetic field. And they also meet the over-pressure requirement. The tritium compatible dosing valve for large flow rate over $60 Pa.m^3/s$ and quick opening time is under exploration. MKS products are considered for other non-tritium dosing valves according to the fuelling rate requirement. Figure 7 shows the latest flow diagram design and the inner structure of GVB based on these candidate valves and components.

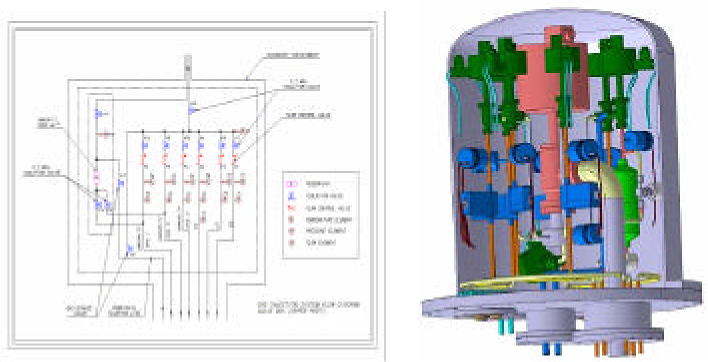


Fig.7 the flow diagram and the structure of upper port GIS

The tritium compatibility and safety operation are important in the GIS design. The work is just initiated through the cooperation with the professional institute in China, which includes the tritium compatible component selection, safety design review, suggestions on the maintenance scheme, emergency protection, sealing, fitting and checking.

The optimization of the structure of GVB and the detailed designs of the straight segment and adaptor in gas supply manifold are emphasis in the next R&D.

4. Summary

Based on the Design Description Document (DDD) of Fuelling and Wall Conditioning System, the design and manufacturing study of the GIS and GDC have been carrying on. The recent progress of the GIS and GDC design is introduced, respectively. The detailed designs of electrode including head structure, fixing component, cooling loop, isolation structure, connector for cooling pipe and power supply cable, interface to the deployment etc., have been carried out. A round shape of the electrode head has been adopted to avoid arcing due to the electric charge in non-uniform distribution on the edge, and special cascade isolation structure has been designed to prevent deteriorating of the isolation performance, arcing and unwanted breakdown. From the point of view of the isolation voltage, irradiation resistant and the manufacture process, the hot pressed ceramic components (99.5% Al_2O_3) are adopted. The ceramic-metal welding insulators are developed and the tests have been done which shows the rationality and reliability of the key components. The transient flow behavior for each working gas has been analyzed. The components of GIS have been investigated and the structure of GVB, which based on the candidate valve and components, has been designed. The preliminary study for the magnetic shield has been done. The prototype of GDC electrode is to be manufactured and the test scheme has been drafted; the tritium compatibility and safety design review of GIS and experimental study of transient flow behavior are expected to be carried on in the near future.

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