Engineering Analysis for Vacuum Vessel of CFQS Quasi-Axisymmetric Stellarator*)

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The world's first quasi-axisymmetric stellarator CFQS (China First Quasi-axisymmetric Stellarator) will be constructed as the joint project of National Institute for Fusion Science (NIFS) in Japan and Southwest Jiaotong University (SWJTU) in China [1]. Physics design of CFQS plasma was completed [2, 3], and numerous efforts are now being made to finalize engineering design of CFQS [4]. The CFQS vacuum vessel (VV) will be made of thin plates of SUS316L with thickness of 6 mm. The thickness is determined by considering fabricability and manufacturing cost. In this report, analyses have been performed to confirm the structural reliability of VV and evaluate the influence of eddy current using finite element method software ANSYS/Mechanical™ and ANSYS/Maxwell™.

Keywords: CFQS, quasi-axisymmetric stellarator, vacuum vessel, eddy current, finite element method

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1. Introduction

The world's first quasi-axisymmetric stellarator CFQS is a low aspect ratio quasi-axisymmetric stellarator based on the concept of a CHS-qa [5]. The device will be sited in the campus of SWJTU, and existing heating systems and diagnostics in NIFS will be transported and utilized to reduce the cost of the project.

CFQS vacuum vessel are major components of CFQS. Its shape is determined mainly by QA (Quasi-Axisymmetric) configuration of plasma, and fairly complicated in shape. It is exposed to several loads, such as atmospheric pressure while keeping inside in a vacuum, electromagnetic force caused by eddy current, and thermal stress during baking. Because the VV will be made of a thin plate of SUS316L with thickness of 6 mm, it is necessary to confirm the structural reliability under these loads.

CFQS coil system consists of 16 modular coils (MCs), 4 poloidal field coils (PFCs) and 12 auxiliary toroidal field coils (TFCs). Current change of these coils will induce an eddy current on the VV, which will produce an electric magnetic force interacting with magnetic fields.

In this report, analyses have been performed to confirm the structural reliability of VV using finite element method (FEM) software ANSYS/Mechanical™ and ANSYS/Maxwell™.

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2. CFQS Coil System

Figure 1 shows schematic view of CFQS coil system. The CFQS has 16 modular coils which produce a magnetic field of up to 1T, and 4 PFCs and 12 TFCs which provide flexibility in the magnetic configuration. As for modular coils, only 4 types of coil shapes are required because of its symmetry. A series of geometry repeats every 90 de-

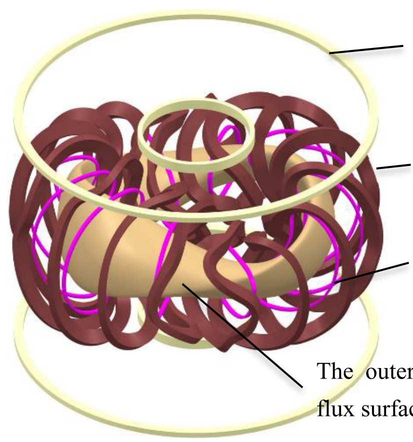

Fig. 1 Schematic view of CFQS coil system.

grees so that the top and bottom sides can be flipped upside down. PFC has two different shapes and TFC three shapes. These are used to move the magnetic axis horizontally and change the rotational transform.

3. CFQS Vacuum Vessel

Figure 2 shows schematic view of (a) CFQS vacuum vessel and (b) leaf-spring type leg. The VV is designed to be manufactured in 4 sections. Each part is made of press formed thin plate. For easy processing and reducing production costs, we have chosen stainless thin plate with a thickness of 6 mm as a material. They will be welded together and installed inside modular coils. Due to its limited access outside VV, the welding should be performed inside. A rectangular port on type A serves as a man access port, and is designed to be large enough for that purpose. We have confirmed the accessibility of the port using 3D printed model.

Besides this port, CFQS VV has many ports as shown in Fig. 2, which are provided for heating and diagnostics. We have limited area where the ports can be mounted because the modular coils will be installed around the VV. Therefore, the sizes and location are determined to make the best use of limited area between modular coils.

The leaf spring type legs serves as support structure of VV. They have leaf-spring-shaped structure literally, and will be installed so as to have flexibility in radial direction. The VV will be baked to about 120°C and expand radially. They can deform to follow the thermal expansion during baking, which is beneficial for reduction of thermal stress.

For the above reasons, these legs should be thinner. However, they should have rigidity not to buckle while ensuring the flexibility in radial direction. Buckling load can

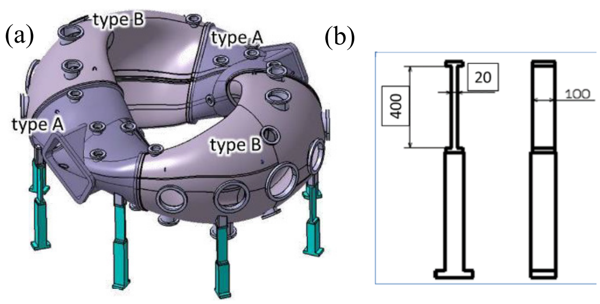

Fig. 2 Schematic view of (a) CFQS vacuum vessel and (b) leaf spring type leg.

Table 1 The values used for calculation of buckling load.

A	0.002 m^2
E	193 GPa
K	0.5
L	400 mm
r	0.00577 m

be calculated by the following formula.

$$\sigma_{cr} = P_{cr}/A = \pi^2 E/(KL/r)^2.$$

In this formula, is the critical stress at which the legs will buckle, E is the elastic modulus of the material, A is cross section area, K is the effective length factor determined by the end conditions of the legs, L is the length of the legs, and r is the radius of gyration, respectively. In Table 1, these values used in this formula are summarized. Therefore, P_{cr} is calculated as follows:

$$P_{cr} = \sigma_{cr} A = 3.17 \times 10^6\ \mathrm{N}.$$

On the other hand, the VV weighs around four tons by accounting for heating and diagnostic devises which will be connected to the ports. The load per one leg is estimated as follows:

$$Mg/8 = 4903\ \mathrm{N},$$

where M is a mass of the VV and g is acceleration of gravity. Therefore, safety factor is obtained by the equation below:

$$P_{cr}/(Mg/8) = 647.$$

According to these results, the buckling may not be problem as for leaf spring type legs.

4. Meshing

In a finite element analysis, a result depends on a condition of meshing, such as an element size significantly. In the structural analysis described in section 6, the solid element is used so as to utilize the design model directly as analysis model. In addition, it is known that three meshes should be applied at least through the thickness when we use solid element for thin plate-like structure. However, we found it impossible to apply such the fine meshes throughout the entire VV. Therefore, we have evaluated the size of solid element small enough to obtain sufficiently accurate result. We have performed a structural analysis in advance using simplified model as shown in Fig. 3, and compare the results of three deferent types of elements including shell element and solid-shell element, which are known as suitable elements for thin plate-like structure. In these analyses, 0.1 MPa is applied on the outer surface as load condition.

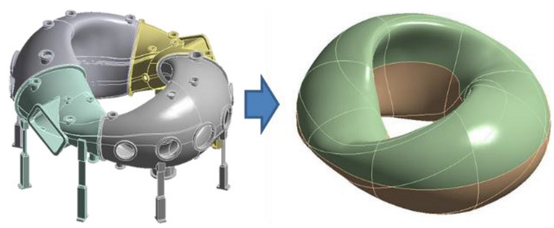

Fig. 3 Simplified model of VV.

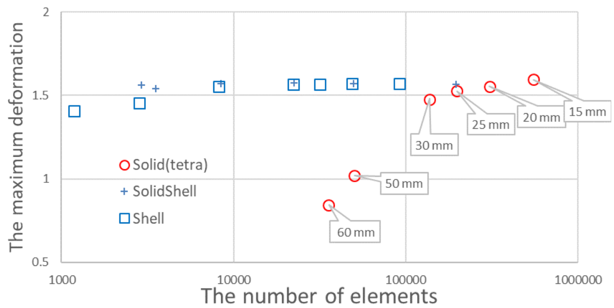

Fig. 4 Comparison of the maximum deformation while changing element sizes.

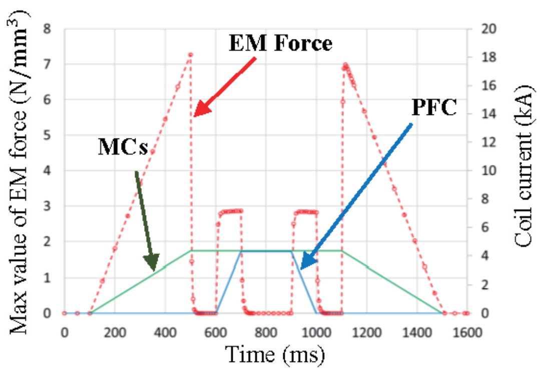

Fig. 5 Time Evolution of Max EM Force on VV and Currents of MCs and PFCs.

Figure 4 shows the result of the analysis. The values beside red circles are element sizes. From this result, at least, 25 mm is sufficient to predict the behavior of the VV.

5. Electromagnetic Force on Vacuum Vessel

In stellarator device, it is assumed that major disruption will not occur since plasma current is not required for confinement unlike tokamak. Therefore, we did not take into account an eddy current caused by disruption events. In this article, an eddy current caused by coil current is considered.

Current change of the coils installed around VV will induce eddy current. The eddy current, interacting with the magnetic fields, induce the EM forces on the VV. To obtain EM force distribution, EM analysis have been performed using ANSYS/Maxwell. The wave form of MCs and PFCs in Fig. 5 are based on operating scenarios in general plasma experiments. The PFC current is defined in the clockwise direction viewed from above and MCs current flows down from the top at the inner region. Time evolution of EM force on VV is also shown in Fig. 5. In this figure, dotted line is spatial maximum value of EM force. According to this result, EM force reaches to maximum value when MCs current is fixed (500 ms in this figure). The value is estimated to be 0.04 MPa. Therefore, it is not negligible compared to atmospheric pressure.

Table 2 Load conditions.

	Atmospheric pressure	Thermal deformation	EM force	gravity
Case 1	○	-	-	○
Case 2	○	○	-	○
Case 3	○	-	○	○

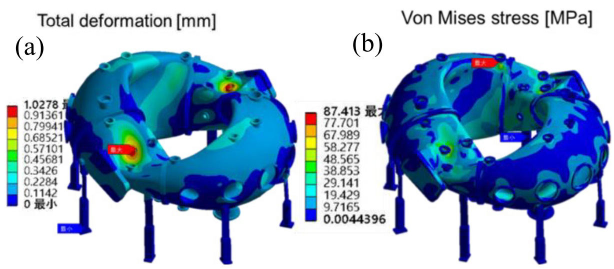

Fig. 6 Results of case 1 (a) deformation [mm], (b) stress [MPa].

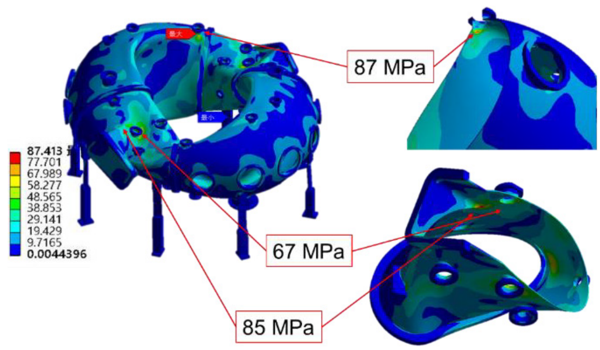

Fig. 7 High stress area in case 1.

6. Structural Analysis of Vacuum Vessel

Analyses have been performed to confirm the structural reliability and behavior of vacuum vessel. The entire VV model is used to prevent uncertainties to use simplified model and to obtain accurate result. Boundary conditions are applied at the bottom surfaces of legs by fixing all degrees of freedom. Table 2 shows load conditions. In case 1, we consider only atmospheric pressure and gravity to clarify the effect of compressive force due to atmospheric pressure at evacuating operation. Figure 6 shows deformation and stress, respectively. The maximum deformation is about 1 mm on the area above the rectangular port. Main component of the deformation is in vertical direction. The most stressed region is between port and VV in which the maximum stress reaches 87 MPa. The stress in similar area is tend to be high as shown in Fig. 7.

In case 2, we added thermal deformation as a load considering baking operation. The VV will be heated up to 130°C during baking, which leads to thermal expansion. The temperature distribution is obtained in advance by thermal steady state analysis in order to prevent discon-

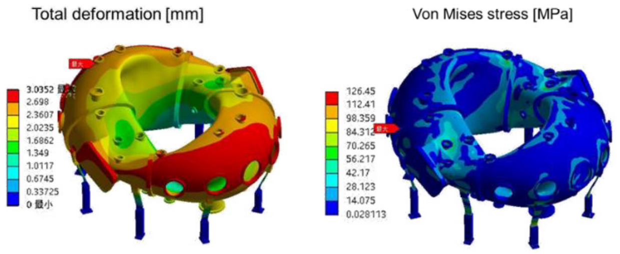

Fig. 8 Results of case 2 (a) deformation [mm], (b) stress [MPa].

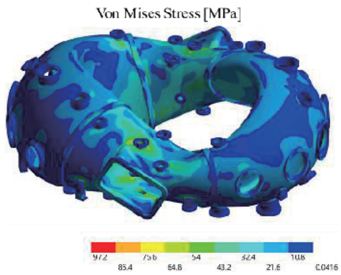

Fig. 9 Results of case 3, stress [MPa].

tinuous distribution, and imported to structural analysis. The primary problem is interference with modular coils that are closely installed around the VV. Figure 8 shows the deformation and stress. The maximum deformation is about 3 mm which appears in the outside of VV, and we can assume that it is mainly caused by thermal expansion considering the result of case 1. The value is tolerable because the minimum distance between modular coils and VV is about 20 mm. Thermal stress is relatively small in most region of VV, and concentrates only in the legs. The maximum stress is 126 MPa in connection between legs and VV, which is below 138 MPa, stress limit of SUS316L at 130°C [6]. A stress calculated by FEM contains several stresses, such as membrane stress and bending stress. We need to restrict stress limit according to a state of the stress. In case membrane stress and bending stress are applied simultaneously, stress limit is allowed up to 1.5 times of design stress.

In case 3, EM force obtained in section 5 is considered. As mentioned in section 5, it is an EM force distribution at the moment when a spatial maximum value reaches the maximum. We found that EM force reaches 40% of atmospheric pressure, and assume that this is the worst case although the wave form shown in Fig. 5 is not optimized one. Figure 9 shows stress distribution. The maximum stress on VV is about 97 MPa which is also acceptable. EM load will occur in the same direction as atmospheric pressure therefore the concern of the interaction between MCs and VV will not be problem in this case.

7. Summary

The CFQS is being constructed as an international joint project between the NIFS and SWJTU. Physics design of CFQS plasma was completed, and a lot of efforts have been put into finalizing engineering design of CFQS.

We evaluated structural reliability of CFQS VV using ANSYS/Mechanical^{TM}and ANSYS/Maxwell^{TM}. we chose three load conditions and clarified the effect of them. Even if we considered atmospheric pressure and EM force simultaneously, in case 3, the maximum value of stress is within an acceptable range. During baking, the VV will expand outward. According to the result of case 2, the maximum deformation is 3 mm on the outside of VV. Because it is lower than the minimum gap between modular coils and VV, the interaction should not be problem.

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