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Design of the Vacuum Vessel for the KT-2 Project

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The design of the vacuum vessel of KT-2(a large-aspect-ratio, mid-size tokamak) is presented. The KT-2 vacuum vessel provides necessary environments to contain a plasma of double-null configuration with elongation of up to 1.8. The vacuum vessel is designed as an all-metal welded structure. Eddy currents are induced on the vessel during all stages of the plasma operation. Influences of the continuous vessel on the plasma were investigated. No significant effect of the vessel on the plasma in every aspect of null formation, plasma initiation, plasma control was found. Stresses and deformations in the vessel by atmospheric pressure and electromagnetic forces due to the eddy currents were calculated using 3D FEM code.

1. Introduction

The vacuum vessel of KT-2 provides necessary environments to contain a plasma of double null configuration with elongation of up to 1.8. The vessel is designed as an all-welded insulator-free structure from stsinless steel with a wall thickness of 12 mm. The vessel consists of four 90 deg. rigid sectors which will be joined together without bellows to form a torus whose major radius is 1.48 m. The vessel has a quasi D-shaped cross section(1.32 m high, 0.85 m wide) which fills the inner bore of the TF maget system. Fig. 1 is the top view of the KT-2 vacuum vessel. Table 1 is the summary of main specifications of KT-2 vacuum vessel.

The toroidal loop resistance is 125 $\mu\Omega$ and the decay time constant of the toroidal vessel current is 15 msec, and in the poloidal direction 14 $\mu\Omega$ and 8.8 msec respectively. Electromagnetic transients occurring during start-up(TF rising, plasma initiation, plasma current ramp-up), shut-down(current ramp-down, TF damping), plasma disruption and displacement induce eddy currents in the toroidal and poloidal directions on the continuous metallic vessel.

The toroidal eddy currents induced on the vessel by an OH loop voltage tend to shield the plasma from the OH voltage itself for the period of the toroidal decay time constant. The eddy currents also produce a vertical field of negative index which obstrut favorable plasma formation, and consequently give the equilibrium field a bad curvature. The long decay time constant of the vessel may cause the delay in controlling the plasma from outside.

TF rising, TF damping and plasma disruption cause large currents and forces in the vessel. Even if eddy currents are induced on the vessel during practically any stage of plasma operation, magnetic forces due to them are most important in the case of the plasma disruption and TF rising because the direction of the forces is the same as that of an atmospheric one. Forces may give rise to a large deformation especially at the edge of a large port hole.

In this paper influences of the continuous vessel on the plasma in the aspects of null formation, plasma initiation, volt-second consumption and plasma control are discussed. Eddy currents and consequent transient magnetic forces due to TF change, plasma disruption and so on are also reported.

2. Influences of the Vessel on the Plasma[1]

If the loop resistance of the vessel is low(the vessel has a thick wall), large eddy currents are induced on the vessel by the change of magnetic fields. The eddy currents may cause difficulty in the plasma initiation, plasma active control and formation of good equilibrium fields. However, the vessel of a thick wall withstands easily large forces acting on it, and has an advantage in controlling vertical plasma stabilities. The upper limit of the wall thickness of the vessel is given by harmful effects on the plasma initiation, plasma active control and equilibrium field, while the lower one is given by considering mechnical strength and passive controllability for vertical stabilities.

Success or failure of plasma initiation through electric breakdowns in the neutral gas depends on whether the ionization rate is larger than the electron loss rate or not. Eddy currents cause two problems. First, they reduce the plasma loop voltage, and the ionization rate drops compared with an original one without the continuous vessel. Second, they form stray error fields which enhance the electron loss rate. Both effects decrease the net ionization rate and give an obstacle to smooth increase of the toroidal plasma current or even make the discharge failed.

Fig. 2 shows the change of coil(Ic), vessel(Iv), plasma(Ip) currents during a start-up for three values of the wall thickness of the vessel with a constant loop voltage of about 18V without considering error fields due to the vessel currents. The vessel currents respond fast to the change of the PF coil currents and increase up to broad peaks and then decrease slowly. The plasma currents start to flow after long delays, but go up very quickly. We recognize easily that main problem is in these discharge delays during which volt-seconds supplied by PF coils are consumed uselessly. The volt-second consumption due to the discharge delays make the plasma flat-top shorten.. Fig.3 shows a volt-second demand curve changing with the thickness of the KT-2 vessel and gives the upper limit of the vessel thickness for obtaining a designed plasma(500 kA, 4.5 sec in OH mode) when the maximum capability of supplying the volt-second is 9.9 v.s.

If the error fields by the vessel currents are taken into account, the probability of the discharge failure becomes high Fig.4 is a chart of success and failure of discharge depending on the vessel thickness(or error field due to the vessel currents). Combining both concepts of Fig 3 and Fig.4, we find that 25 mm is the maximum allowable wall thickness of the KT-2 vessel to initiate plasma without failure and to maintain the plasma of 500 kA for 4.5 seconds.

The eddy currents flowing on the vessel also may affect formation of a magnetic null, evolution of plasma equilibrium, active plasma control and passive control of plasma vertical stability. No significant difference between two magnetic null configurations at the end of bias phase with and without passive structures like the vessel was found in TSC calculations. TSC simulations also showed that there were no harmful effects of the KT-2 vessel on the equilibriums in the period of operating plasma mode change from a limiter mode to a divertor mode. Active and passive contollability of plasma was not influenced by the KT-2 vessel, and the plasma control was satisfactorily done in a time constant of 5 msec.

3. Impacts on the Vessel during KT-2 Operations

The vacuum vessel is under influences of various forces acting on it during a plasma operation. The atmospheric pressure of 1 kg.f/cm^2 is applied continuously on the vessel all the machine operation time. During TF rising and damping stages poloidal vessel currents are induced, and they give rise to forces in the vessel radially by interacting with TF. If the plasma loses the energy contained in it, the plasma current starts to drop and the plasma column moves to the direction of a small major radius. If there is a loss of control due to the fast progress of above procedures, plasma is led to a disruption. During a hard disruption a large toroidal vessel current even comparable to a plasma flat-top current is produced by the fast magnetic field change. The toroidal vessel current interacts with the poloidal field and produces normal force on the vessel itself. In addition to the toroidal vessel current, a poloidal vessel current is also induced by diamagnetic effect of TF due to the plasma beta change during a plasma disruption.

The forces produced by the atmospheric pressure, TF change and diamagnetic effect can be derived and estimated analytically by hand calculations. The eddy currents due to the current quench and the column displacement during plasma disruptions are localized depending on the final position of the normal plasma and the moving directions. Therefore, they can be obtained by only a numerical analysis, even if we can estimated analytically a total effect of current quench[2].

To calculate eddy currents on the vessel during plasma disruptions, the vessel was simulated as 30 discrete segments. Eddy currents on the 16th segment(small major radius side on the mid plane) were usually the maxima of the current distributions on the 30 segments, and were estimated to be around 45,000A at peaks.

The forces induced on the vessel may have different time domains depending on their origins and operating modes. Certain two forces overlap with each other, but other two forces may be independent of each other. Besides differences in the time domain of the forces, their directions acting on the vessel vary by case. Some forces add together, but certain forces may cancel other forces. Fig. 5 shows schematically directions of various forces exerted on the vacuum vessel. Table 2 is the summary of the pressures acting on the KT-2 vessel and resulting total radial and vertical force components.

Stresses and deformations by the forces induced in the vessel were calculated using a 3D FEM code. Fig. 6 is the result of the stress analysis of KT-2 vessel in the TF rising stage as the worst case in the KT-2 operating modes. The maximum stress was less than 35 MPa at the inner cylindrical part, while the maximumdeformation was about 0.32 mm at the large access port.

[1] S.R.IN, Ungyong Mulli(The Korea Physical Society),*8*,449(1995)
[2] P.Noll,et al., Fusion Tech.,*15*,259(1989)

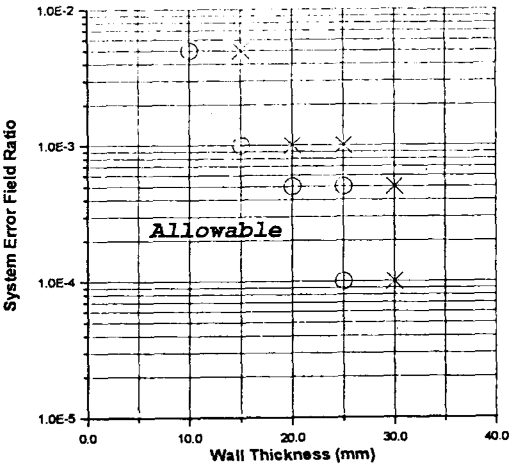

Fig. 4. Chart of Discharge Success(O) and Failure(X).

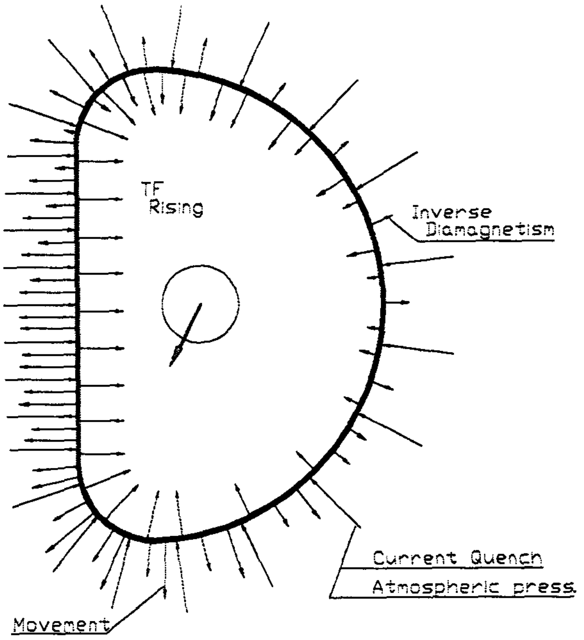

Fig. 5. Direction of Forces acting on the Vacuum Vessel.

Table 2. Forces acting on the KT-2 Vessel.

	Pressure(kg.f/cm2)	F_r(radial)/ F_v(vertical)(ton.f)
Atmospheric pressure	-1	-58 (F_r: inward)/ -79 (F_v: compression)
T.F rising	$-0.24/R^2$	+10.5 (outward)/ -9 (compression)
T.F damping	$+0.42/R^2$	-18.5/ +15.5 (tension)
Plasma Disruption(~2ms) Diamagnetic change		
$\beta = 0$	$+0.29/R^2$	-13/ -11 (compression)
$\beta = 2$	$-0.29/R^2$	+13/ -11
Current quench	Max. -0.55	-12.8
Vertical Displacement	N.A	10
Halo current	Max. +0.56	N.A

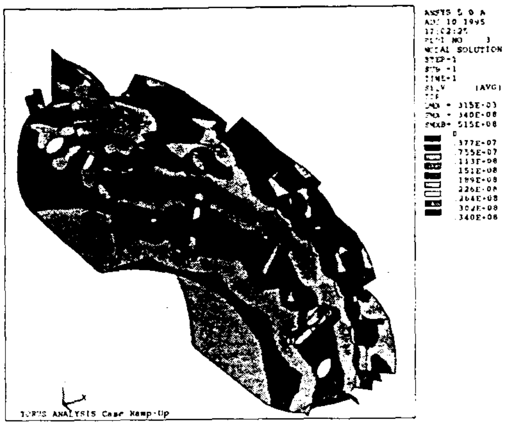

Fig. 6. Stress Distribution in the Vessel during a TF rising Stage.

Table 1. Specifications of the KT-2 Vessel.

Parameters	
Cross Section	quasi D shape (one straight, 3 arcs)
Inner major radius	1062 mm
Inner width	846 mm
Inner height	1316 mm
Inner total area	~29 m^2
Protected area	~27 m^2
Effective protected area	~22 m^2
Volume	~9 m^3
Material	S.S 304L
Wall thickness	12 mm
Toroidal inductance	1.88 μH
Toroidal resistance	125 μΩ
Toroidal decay time(τ_{tor})	15 msec
Poloidal inductance	0.123 μH
Poloidal resistance	14 μΩ
Poloidal decay time(τ_{pol})	8.8 msec
Weight	~4 ton

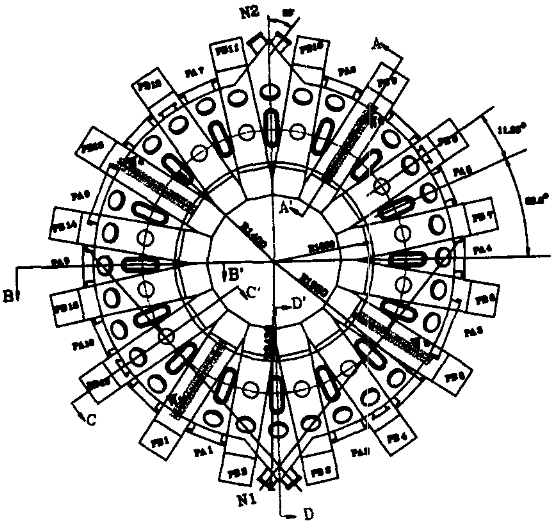

Fig. 1. Top View of the KT-2 Vessel.

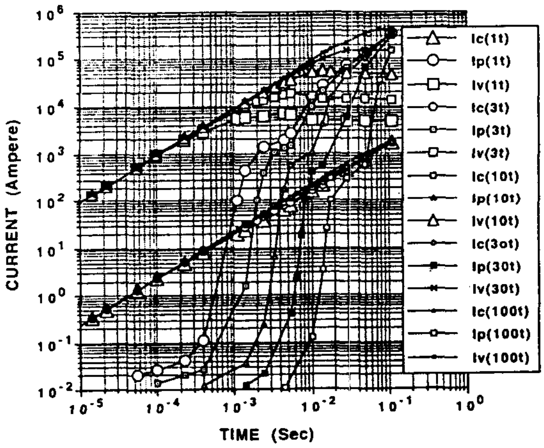

Fig. 2. Change of the Coil(Ic), Vessel(Iv), and Plasma(Ip) currents.

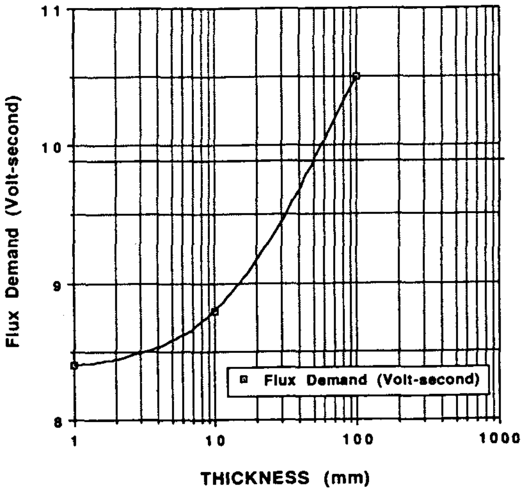

Fig. 3. Demand of Magnetic Flux depending on the thickness of the KT-2 Vessel