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Structural Analysis of First Wall/Blanket Vessel for a Tokamak Power Reactor

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The first wall/blanket vessel of a Tokamak Power Reactor which aims at generating electric power economically is subjected to high heat load resulting in high operating temperature. Long lifetime of the reactor and high reliability of its operation are generally required on a structural design of the Power Reactor.

Several fundamental shape of structures have been proposed to date as the design of the first wall subjected to high surface heat flux. In our design of the Tokamak Power Reactor among them, a tube panel configuration, which seems the most desirable to resist a coolant pressure, has been selected as the first wall structure.

The average neutron wall loading of the first wall is 3.3 MW/m^2 and then the surface heat flux is 0.8 MW/m^2. Light water is adopted as the coolant under a pressure of 16 MPa and inlet and outlet temperatures of the coolant are 290°C and 330°C, respectively. Titanium modified austenitic stainless steel serves as the structural material of the first wall/ blanket vessel. The dimensions of the first wall/blanket vessel has been determined under the operating thermal conditions. The maximum operating temperature of the structural material has been limited below 800°F(427°C) so as not to generate a remarkable inelastic strain.

Thermal and stress analyses have been conducted under the steady state operating conditions. Since the power reactor is designed to operate in a steady state mode, thermal fatigue damage is considered small and so its analysis is not needed to be done here. The stresses caused in the first wall/blanket vessel are shown to satisfy the design criteria of ASME Boiler and Pressure Vessel Code Sec.III at least if not taking account of the effect of neutron damage.

On the other hand, the time constant of the plasma disruption is much smaller than for heat conduction and therefore the disruptions will cause surface heating generating the high thermal stress in a thin layer of the first wall. A temperature rise at the surface of the first wall is strongly dependent on the disruption mode. Since the actual experimental data is absent at present, the thermomechanical characteristics of the first wall, to which coating material may be attached or not, has been estimated preliminarily under several disruption modes.

INTRODUCTION

This study has been performed for the first wall/blanket vessel of the Tokamak Power Reactor (SPTR-P)(1),(2) being designed at JAERI. The average neutron wall loading is 3.3 MW/m^2 and the surface heat flux of the first wall is 80 W/cm^2. The nuclear heating rate of the first wall made of stainless steel is 36 W/cc.

Since the first wall is subjected to such a high heat load, the thick plate structure is hardly adopted at the first wall from viewpoints of thermal stress. Several first wall concepts(3), such as ribbed panel, embossed panel and tube panel, have been proposed at the present in order to avoid a large thermal stress. Among them, the tube panel configuration as shown in Fig. 1, which seems the most desirable to resist a coolant pressure, has been selected as the first wall structure for this study.

The first wall is separated from the blanket and supported on the plasma-side wall of the blanket vessel. There is a disadvantage in this separated-type first wall, since the effective thickness of the structural material and coolant increases in front of the breeding material which results in the decrease of the breeding ratio. The separated-type first wall is however desirable to obtain a sufficient structural strength and high reliability in a high temperature operation. The first wall/blanket vessel of this power reactor has been designed with emphasis on the structural strength. The net tritium breeding ratio over unity is obtained by using a beryllium as a neutron multiplier.

Key design parameters are: fusion power of 3200 MW, net electric power of 1000 MW, average neutron wall loading of 3.3 MW/m^2, major radius of 6.9 m , plasma radius of 2.0 m, plasma elongation of 1.6, plasma current of 16.0 MA and toroidal field on axis of 5.2 T.

THERMAL AND HYDRAULIC ANALYSIS

The first wall/blanket vessel is cooled by a pressurised water of 16 MPa in view of the generation of an electric power and its inlet/outlet temperature is 290/330°C. PCA(titanium modefied stainless steel) serves as the structural material and its maximum operating temperature is restricted below 800°F (427°C).

The thickness of the first wall is mainly limited by the temperature difference through the wall due to the surface heat flux of 80 W/cm^2. From the thermal and hydraulic calculation based on a cylindrical model, the inner radius of 5.0 mm and the thickness of 1.5 mm are determined for the first wall tube. In the selection of the structure, the maximum temperature of the first wall, the heat transfer and pressure loss of the coolant and the ratchet strain rate at a high temperature range are considered.

The average length of the first wall is 4.0 m. The variations of the maximum temperature, film temperature drop and heat transfer coefficient are shown in Fig. 2 as a function of the coolant velocity. The coolant velocity required is 3.6 m/sec.

The length of the first wall depends upon the number of the reactor modules and its assembling design. In this design, the torus structure is divided into 32 modules in terms of 16 toroidal magnetes and each module is classified into the inboard and the outboard sections which consist of several first wall/blanket vessel segments. Figure 3 shows the reactor module. The length of the first wall tube in the poloidal direction at the inboard section will be about 6.0 m since each blanket module is segmented in the toroidal direction of the torus. On the other hand, since each blanket module at the outboard section is segmented in the poloidal direction, the first wall tube is installed in the toroidal direction of which the length will become to be about 1.8 m on the midplane. It is necessary to increase the surface area recieving the surface heat flux on the first wall at the outboard section and to keep the inlet/outlet temperature difference 40°C by the reasonable coolant velocity. The surface area may be increased if a few segments of the first wall are joined with header and so on. The length of the first wall is considered for 3.0∿6.0 m. The variations of the inlet/outlet temperautre difference are shown in Fig. 4 as a function of the first wall length and the coolant velocity. In order to keep the temperature difference constant, the flow control of the coolant corresponding to each length of the first wall should be required taking into account of the allowable maximum temperature (800°F/427°C) of the first wall.

In the present analysis, the heat load due to nuclear heating has been neglected. When the heat load estimated be about 20∿30% of the surface heat flux is considered, the coolant flow will increase at the same rate.

THERMOMECHANICAL DESIGN

The configuration of the first wall/blanket vessel is shown in Fig. 5. The first wall is basically a cylindrical structure and is assembled with semicircular tubes of which the side supported on the blanket is flat. In order to construct a tube panel, each tube is joined mutually and is fixed on the flat board. Whether this flat board should be attached on all over the backside surface of the tube panel or on only the support region depends upon the length of the first wall and the joining structure of the adjacent tubes. The vibration and the fretting behaviors produced by the high coolant velocity should be also considered. Since the thickness of the blanket is 50 cm, it will be sufficient to fix partially the tubes with a band plate and/or to join the adjacent tubes with a welding at both the side of the blanket vessel. The tubes for cooling the blanket vessel wall are the same size as the first wall tubes. The coolant flow direction of the blanket vessel wall tubes is perpendicular to that of the first wall tubes and of the cooling tubes in a breeding material region. The thickness of the blanket vessel wall should be determined to withstand the pressure of a helium purge gas (0.1 MPa) at least.

The support region should be sufficiently cooled in the separated type of the first wall. The optimum thickness of the support region has been determined from the heat transfer analysis so that the maximum temperature of the support region is restricted below 427°C.

The heat transfer analysis has been conducted by two dimensional model that the coolant flow direction of the first wall is parallel to that of the blanket vessel wall. This model is applicable to select the fundamental structure of the first wall since there will be no significant difference in the maximum temperature in comparison with the results obtained by the three dimensional model. The thickness of the blanket vessel wall is 12.5 mm. The half part of the cooling tube is put into the blanket vessel wall and is fixed by brazing and/or welding. The maximum temperature of the support region is below 427°C if the thicknesses of the plate supporting the adjacent tubes and that of the pedestal supporting the tube panel are about 5.0 mm, respectively. Figure 6 shows the temperature distribution around the support region. The analytical conditions are as follows: the velocity of the first wall coolant is 4.0 m/sec, its heat transfer coefficient is 29,000 $W/m^2 \cdot K$, the heat transfer coefficient of the blanket vessel wall coolant is $42,000/m^2 \cdot K$ and the maximum nuclear heating rate is 36 W/cc.

The analysis has been conducted under the condition that the coolant dose not boil at the inside surface of the tube. The coolant may however locally boil as shown in Fig. 6 and then the temperature at the plasma side will decrease.

The two dimensional model employed in this analysis is sufficiently applied to estimate the temperature at the support region. However, it may not appropriate to apply this model to the stress analysis since two different directions of the coolant flow and the real three dimensional boundary conditions can not be considered. Nevertheless, from the results obtained by the stress analysis using the present model, it is possible to estimate the stress generating at the support region. Figure 7 shows the distribution of the stress intensity under the coolant pressure and the thermal load. The longitudinal stress is neglected in the present stress analysis. A large longitudinal stress may not generate since the temperature difference is not very large, the supporting pedestal on the blanket vessel is locally attached and the deformation due to thermal expansion is allowed to some degree.

In general, the temperature difference between the face and back of the first wall, which generates by the unilateral surface heat load, has become one of the problems on the thermomechanical design of the first wall. The present analytical model is considered to be reasonable for the conceptual design selecting the foundamental structure of the first wall/blanket vessel, though the detailed structure including the support should be determined from a three dimensional model.

The power reactor is assumed to operate the steady state mode and the thermal fatigue damage will be small. A little larger thermal stress may be allowed if there is no damage effect on the creep and the maximum temperature is restricted below 800°F(427°C).

TRANSIENT HEAT TRANSFER ANALYSIS

A large plasma energy (thermal and magnetic energy) is released to the first wall at the moment of the plasma disruption. The energy released may bring about the severe condition for the first wall design. However, the spacial and temporal modes of the disruption have not been yet established for lack of the detailed experimental data.

The thermal energy of this power reactor and the area of the first wall are estimated to be about 900 MJ and 800 m^2, respectively. When the thermal energy of 900 MJ is released at the disruption according to the scenario adopted in the INTOR, three cases for the peak heat load are estimated as follows:

1 —— 572J/cm^2 .... in INTOR Phase I(4)
2 —— 52J/cm^2 .... in INTOR Phase IIA(5)
3 —— 263J/cm^2 .... in INTOR Phase IIA(5)

In the cases of the later 2 and 3, the rest of the energy is released to the limiter.

Since the time constant of the disruption for the power reactor is expected longer than that for the experimental reactor, the time constant is assumed to be 50 msec here and the heat load to the first wall during the disruption is expected to decrease exponentially.

As one of the measures to prevent the first wall from being high temperature at the disruption, the coating on the plasma side of the first wall is adopted in this design and Graphite is employed as the primary candidate material.

Figure 8 shows the results of the transient heat transfer analysis(6) for the energy density of 572 J/cm^2. As shown in Fig. 8, the thickness of the graphite affects very sharply the temperature of the first wall. The surface temperature of the graphite reaches about 1500°C for the time constant of 50 msec and its temperature is below the melting point. However, the temperature of the first wall (stainless steel) reaches 700∿1000°C. Since a large thermal stress may generate at the contact region between the stainless steel and the graphite, the detailed thermomechanical calculation and the development of the coating technique to reduce the thermal stress should be required.

In the two cases that the energy densities are 52J/cm^2 and 263J/cm^2, the transient heat transfer analysis has been conducted for the first wall of the bare stainless steel without the graphite coating. Figure 9 shows the maximum temperatures at the plasma side and the coolant side of the first wall. Even if the time constant is 200 msec, the maximum temperature of the first wall reaches about 770°C for the energy density of 263J/cm^2. When the stainless steel serves as the structural material of the first wall, the thermomechanical design of the first wall may become severe in the range of its temperature with the bare stainless steel. The coating may be required on the plasma side of the first wall. On the other hand, the maximum temperature of the first wall reaches about 560°C for the energy density of 52J/cm^2. If the lower energy density of 52J/cm^2 is released to the first wall at the disruption, the temperatures of the stainless steel are below the allowable limit of the thermomechanical design. In such a condition, however, the rest of the plasma energy is released to the limiter plate as a large heat load and then the thermomechanical design of the limiter will become very difficult.

The energy distribution and the time constant at the disruption affect directly the thermomechanical designs of the first wall and the limiter. Therefore, it is required to pursue the disruption physics study of decreasing the local heat load on each component, increasing the time constant, reducing the frequency and preventing the disruption, if possible.

THERMO-ELASTIC-PLASTIC STRESS ANALYSIS

When the 50% of the thermal energy is released uniformly to the first wall, its energy density is 52J/cm^2 which is an acceptable heat condition for the first wall design. In this case, the coating material may not be required.

The thermal and stress analysis for the first wall have been conducted under the energy density 52 J/cm^2 and the time constant of 50 msec. Figure 10 shows the temperature change through the wall at each time during 0∿40 msec. The plasma side of the first wall indicates the rapid temperature rise because of the surface heating at the disruption. Its temperature reaches 560°C at 40 msec. On the other hand, the coolant side reaches 360°C. The temperature difference through the wall is about 200°C.

The structural material of the stainless steel will exceeds the yield strength under such a thermal load and the coolant pressure of 16 MPa and will also indicate the elastic-plastic behavior. The thermo-elastic-plastic analysis of the first wall has been conducted by the axisymmetrical model. The material constants of Type 316 stainless steel as shown in table 1 are considered. Figure 11 shows the distribution of the hoop stress through the wall at the three load conditions (coolant pressure, steady state operation and disruption). As shown in Fig. 11, the elastic-plastic state at the coolant side of the first wall has been indicated even at the steady state operation. Figure 12 shows the hoop strain-stress relation. Even if the relatively low energy density of 52J/cm^2 is released at the disruption, the equivalent plastic strain more than 0.1% generates in the first wall. If the accumulated ratchet strain increases the allowable frequency of the disruption during the lifetime will be restricted.

Since the maximum temperature of the first wall is designed to be restricted below 427°C during the operation, the high temperature creep strain may not affect the lifetime.

However, the neutron damage affects significantly the lifetime of the first wall and should be considered to evaluate the detailed lifetime. We should carry out the thermomechanical structural design of the first wall/blanket vessel which has enough mergin against the neutron damage.

CONCLUSION AND REMARKES

Many concepts of the first wall structure has been proposed at the present. In our design, a separated-type first wall consisting of the tube panel, is employed from viewpoints of good fablicability and high feasibility. The thermomechanical design has been carried out so that the first wall/blanket vessel has enough structural strengh. However, the detailed support design is left in the future study.

The heat load at the disruption will make the thermomechanical design of the first wall severe. In future are requried a progress of the plasma physics which reduces the frequency, increases the time constant and reduces the local heat load and the establishment of the coating technique for low Z materials.

The rectangular shaped-blanket vessel is selected from viewpoints of its high feasibility. The piping layout of the first wall/blanket vessel, the coolant velocity, the length of the cooling path and the coolant flow direction shoule be designed to satisfy the cooling conditions (inlet/outlet temperature 290/330°C, etc). The layout of the main piping and the headers, which are contained in the bore of the toroidal magnets, should be also designed in detail taking into account of the repair and maintenance.

ACKNOWLEDGEMENTS

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Table 1 Material constants of Type 316 S.S.

Temp. T(°C)	Yield Strength σ_y (MPa)	Young's Modulus E(GPa)	Tangent Modulus H(MPa)
300	163	180	3578
400	156	171	3446
500	148	162	3318
600	141	152	3180

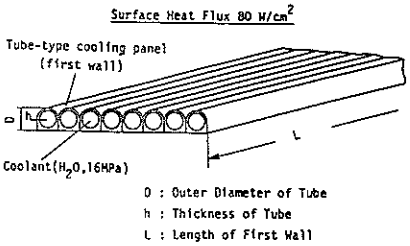

Fig.1 Configulation of first wall

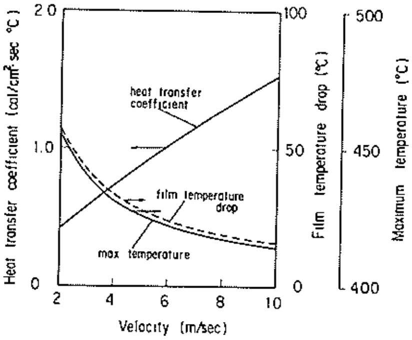

Fig.2 Effect of coolant velocity

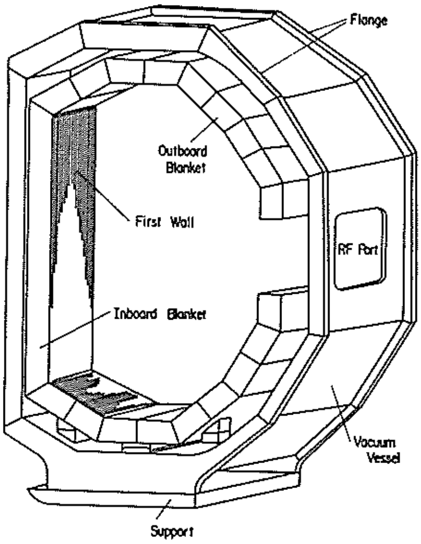

Fig.3 Reactor module

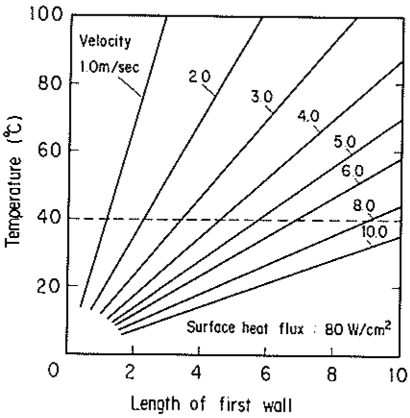

Fig.4 Difference of inlet/outlet temperature

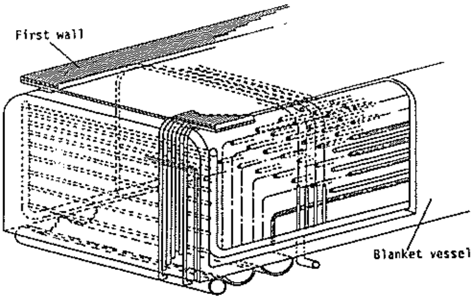

Fig.5 Configulation of first wall/blanket vessel

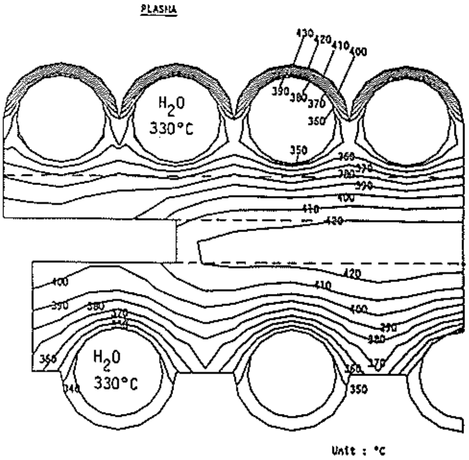

Fig. 6 Temperature distribution

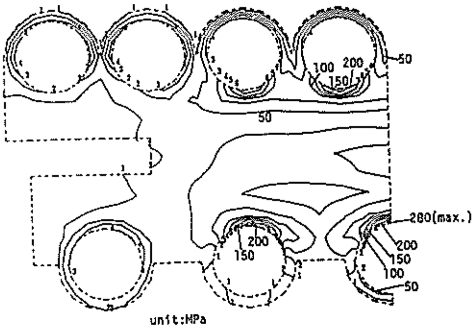

Fig.7 Distribution of stress intensity

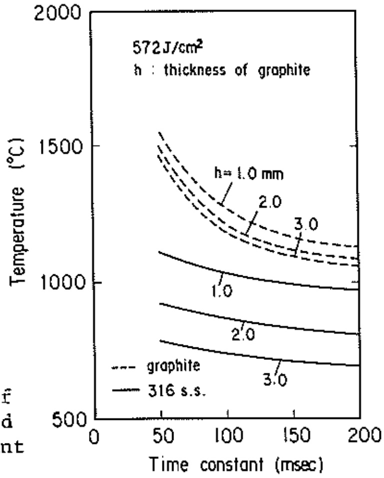

Fig.8 Effect of thickness of graphite and time constant

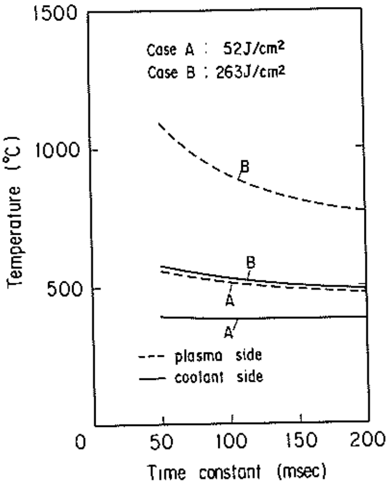

Fig.9 Effect of time constant

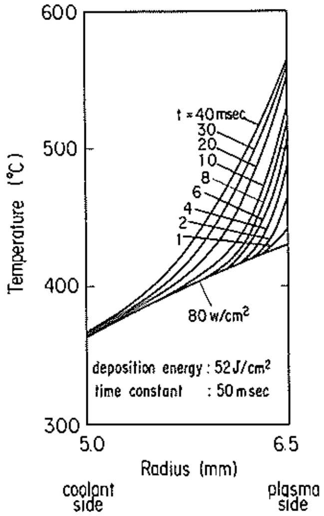

Fig.10 Temperature distribution through wall

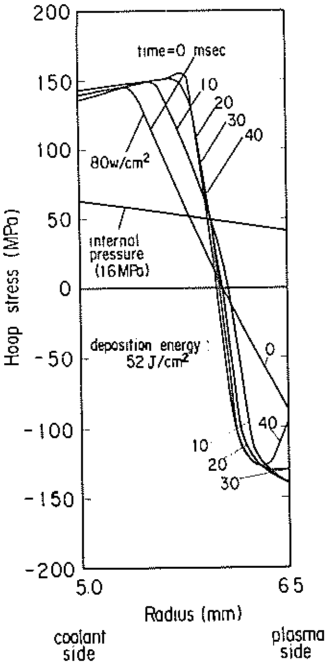

Fig.11 Distribution of hoop stress through wall

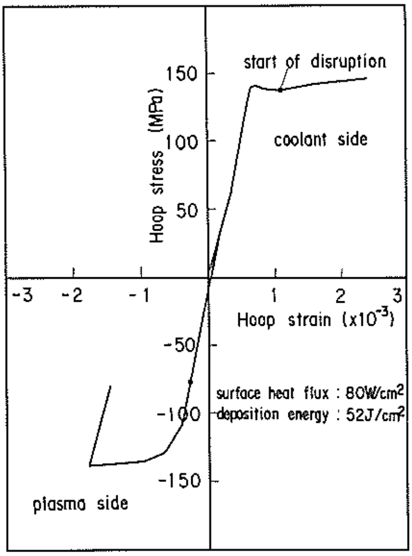

Fig.12 Hoop strain-stress relation