Conceptual Design of Vacuum Chamber for testing of high heat flux components using electron beam as a source

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Abstract. A conceptual design of vacuum chamber is proposed to study the thermal response of high heat flux components under energy depositions of the magnitude and durations expected in plasma fusion devices. It is equipped with high power electron beam with maximum beam power of 200 KW mounted in a stationary horizontal position from back side of the chamber. The electron beam is used as a heat source to evaluate the heat removal capacity, material performance under thermal loads & stresses, thermal fatigue etc on actively cooled mock – ups which are mounted on a flange system which is the front side door of the chamber. The tests mock – ups are connected to a high pressure high temperature water circulation system (HPHT-WCS) operated over a wide range of conditions. The vacuum chamber consists of different ports at different angles to view the mock-up surface available for mock -up diagnostics. The vacuum chamber is pumped with different pumps mounted on side ports of the chamber. The chamber is shielded from X – rays which are generated inside the chamber when high-energy electrons are incident on the mock-up. The design includes development of a conceptual design with theoretical calculations and CAD modelling of the system using CATIA V5. These CAD models give an outline on the complete geometry of HHF test chamber, fabrication challenges and safety issues. FEA analysis of the system has been performed to check the structural integrity when the system is subjected to structural & thermal loads.

1. Introduction
The Divertor is one of the key components of the TOKAMAK. Its function is to extract heat and helium ash (the products of the fusion reaction) and other impurities from the plasma. It comprises of mainly two parts viz. a supporting structure made primarily from stainless steel and the plasma-facing component. A cross-sectional view of ITER Tokamak is shown in figure 1. The Plasma Facing Components (PFC) will be made of tungsten and Carbon Fiber Composites (CFC). Plasma facing materials have to withstand particle and heat loads from the plasma and neutron loads during reactor operation [1-2]. A broad spectrum of high heat flux test facilities are being used worldwide to investigate the thermal response of plasma facing materials and components to fusion relevant thermal loads [3-4]. These tests cover both normal operation scenarios with cyclic thermal loads and power densities in the range of several MW/ m² and transient heat load tests to simulate short events such as edge-localized modes, plasma disruptions and vertical displacement events.
2. Objectives of High Heat Flux (HHF) test facility

The primary objectives of HHF test facility is to provide the condition needed to evaluate the performance of PFMs and plasma facing components, under ITER specific thermal loads i.e. quasistationary heat fluxes up to approximately 10MW/m² (< 20MW/m² during slow transients for a duration of <10s) and sufficiently large number of cycles. To verify heat transfer coefficients/correlations currently in use by comparing finite-element calculations with measured temperatures. A secondary objective will be to collect enough data on temperature distribution in the test module so that future calculation of heat transfer coefficients by inverse conduction analysis is possible. A schematic of the proposed high heat flux test facility at IPR (HHF test facility) is shown in figure 2 and different types of HHF components with testing parameters are shown in Table 1.

| High heat flux components | ITER Divertor |
|---------------------------|--------------|
| **Design**                | Flat tile    |
|                           | Brush        |
|                           | Monoblock    |
| **Heat flux**             | Average MW/m²|
|                           | Maximum MW/m²|
| 3-5                       | 10-20        |
| Maximum heat load MJ/m²   | 10           |
| Life time Years           | 3            |
| No. of full load cycles   | 3000         |
| Neutron damage dpa        | 0.2          |
| Structure material        | CuCrZr & CFC/W|
| Coolant                   | Water        |
| Pressure MPa              | 4            |
| Temperature °C            | 100 – 150    |
| Velocity m/s              | 9 – 11       |
| Leak rate g/s             | < 10⁻³       |
3. Worldwide HHF Test Facility

In order to study the effect of these high heat loads, several electron beam-testing facilities in different countries have been utilized for testing of high heat flux components of next step fusion devices. In principle all the testing facilities are comparable. They consist of an electron gun, a beam sweeping system, a vacuum chamber in which samples can be inserted, and a number of diagnostic devices. However, some machine parameters are quite different. Table 2 represents the comparison study on various electron beam facilities worldwide based on different parameters listed in table 2.

Table 2: Machine parameters for the electron beam facilities all over the World [3-4]

| FACILITIES  | JUDITH 2 | JEBIS | TSEFY | FE 200 | EBTS | EB 1200 | IPR |
|------------|----------|-------|-------|--------|------|---------|-----|
| Max voltage (KV) | 30-60    | 100   | 30    | 200    | 30   | 40      | 45  |
| Max current (mA)  | 4000     | 4000  | 2000  | 1000   | 1000 | 30000   | 4444|
| Max power (KW)    | 200      | 400   | 60    | 200    | 30   | 1200    | 200 |
| Max heated area (m²) | 0.25     | 0.18  | 0.25  | 1.0    | 0.10 | 0.27    | 0.16|
| Beam generation   | Thermal emission | Plasma discharge | Thermal emission | Thermal emission | Thermal emission | Thermal emission |
| Particle type     | e⁻       | e⁻    | e⁻    | e⁻     | e⁻   | e⁻      | e⁻  |
| Power density (GWm⁻²) | 10       | 2     | 0.2   | 60     | -    | 10      | 1.2 |

4. Different subsystems

(a) Vacuum Chamber

(b) Electron beam equipment

(c) Different types of diagnostic

Here, we will discuss only about conceptual design of Vacuum chamber. We have chosen a D-shape vertical chamber as it reduce the volume, surface area as compare to horizontal cylindrical chamber. Electron gun is projected horizontally from backside and will be supported separately with a separate arrangement. The dimensions of the chamber are assumed to be of diameter 2.4 m, height 1.5 m with double wall cooling system to accommodate full-scale mock-up for testing. Conceptual design of D–shape double wall vertical chamber is shown in figure 3. The mounting arrangement for mock – up is designed in such away that it is supported from outside such that weight of the mock – up is not coming on to the chamber. A front door flange with cantilever support plates is designed and shown in figure 4. The supporting structure for the chamber is designed to be a flat surface with leg type support. The position of diagnostic ports are designed in such away that all the ports can view the total area of the mock – up such that the data at any point on the mock – up can be easily done through the diagnostic devices.
For the positioning the different ports, the semicircular area of the chamber is divided into 15° angles and is projected vertically. On each 15° axis, the angular position of ports are done based on viewing the port at a particular point, such that all the ports through out the circumference are projected at particular points at the front end which makes easy observation during experiment. The front door flange is used for mounting PFC with the help of cantilever support plate and the PFCs are masked with copper blocks. The distance between mock – up and electron beam point is calculated to be of 1.7 m such that the beam can raster the total surface area of the mock – ups of different sizes ranging from small scale to large scale.

5. Design procedure for cylindrical shell

The required thickness of cylindrical shell or tube exclusive of corrosion allowance under external pressure either seamless or with longitudinal butt-welded joint as per ASME Boiler and Pressure Vessel Code Section VIII Division [5] is determined and shown in table 3.

Table 3: Design parameter for Shell thickness and Flat head

| S.No | Parameter                                   | Unit       | Value       |
|------|--------------------------------------------|------------|-------------|
| 1.   | External pressure                          | Pe         | 1.013/14.7  |
| 2.   | Temperature                                | T(°C)      | 27          |
| 3.   | Material for construction                  |            |             |
|      | • Shell plates, flanges, blanks: ASTM/ASME |            |             |
|      | SA 240 Grade SS 304L                       |            |             |
|      | • Collar for the rectangular front plate:  |            |             |
|      | forged plate F304L                         |            |             |
|      | • Reinforcing bars (channel) made from     |            |             |
|      | plates of ASTM/ASME SA 240 Grade SS 304L   |            |             |
|      | • Column: MS channels of IS2062             |            |             |
| 4.   | 1st assumed thickness (due to external     | ta (mm)    | 8           |
|      | pressure)                                  |            |             |
| 5.   | Unsupported length                          | L (mm)     | 1500        |
| 6.   | Outside diameter                           | Do (mm)    | 2400        |
| 7.   | Allowable pressure Pa = 4B/(3(Do/t)), where | Pa(PSI)    | 52.44, Safe |
|      | t = ta                                     |            |             |
| 8.   | Provided thickness                         | tp (mm)    | 12          |

5.1 Static FE analysis

Results of finite element analysis consist of nodal displacements and element stresses. The structural analysis has been made by means of CATIA V5 R18 “Generative Structural Analysis tool”. The aim of this analysis is to determine the structural stress distribution in the system. Data used for structural analysis is shown in table 4 and the results of structural analysis are shown in figure 5a and figure 5b.

Figure 5(a) VonMises stress in Pa

Figure 5(b) Total deflection in mm
Table 4: Data used for structural analysis

| Structural analysis: CATIA V5 R12 Generative Structural Analysis tool |
|---------------------------------------------------------------|
| Material | SS 304L for chamber and mild steel for the chamber |
| Element type | Solid 185 having three (3) degrees of freedom |
| Boundary conditions | • External surface load: pressure 1x10^5 Pa  
   • Gravity load  
   • Lower key points for support columns as a fix point |
| Vector sum deflection | 1.3 mm |
| Von Mises stress Max | 30.05 MPa, within the yield strength of the material and is safe |

| Radiation analysis: ANSYS 12 |
|-------------------------------|
| Method | AUX 12 radiation matrix generator method |
| Element type | Solid Tet 10 node 87, Shell 57 with temperature as a one degree of freedom |
| Radiation surface | PFC and VV |
| Boundary conditions | • Temperature on the surface of PFC 1773 K  
   • Space temperature: 300 K |
| Maximum surface temperature | 643.7 K |

5.2 Thermal Radiation analysis

Thermal responses of the PFC and VV during electron beam operation have been calculated analytically and 3-D finite element analysis using ANSYS. All the ports, which are attached to the chamber, are ignored and heat flux is calculated. In the FE model the radiation is included through the use of AUX 12 radiation matrix generator method. The radiation matrix is calculated on the basis of the Stefan – Boltzmann law of radiation. The maximum surface temperature of the chamber is found to be 643.7 K. Results are shown in figure 6(a) and figure 6(b).

5.3 Vacuum Pump calculations

The pump down time ($\tau$) from the initial (atmospheric) pressure to the working pressure of the system is to be calculated for a given volume of chamber (litre) with a given pumping speed ($S_p$) of a particular pump. The ultimate pressure ($P_u$) in the chamber can be expressed as

\[ P_u = \frac{Q_g}{S} = \frac{(Q_g/V)}{(V/S)} = \frac{Q_g}{V} \frac{1}{S} P = \frac{\Delta P}{\Delta t} \] \hspace{1cm} (1)

Where $Q_g$ is the total gas load, $V$ is the volume of chamber, $S$ is the pumping speed in chamber and $C$ is the conductance of an elbow

\[ \frac{1}{S} = \frac{1}{S_p} + \frac{1}{C} \] \hspace{1cm} (2)

And

\[ C = 3.81 \sqrt{\frac{T}{M}} \frac{D^3}{(L_1 + L_2)} \] \hspace{1cm} (3)
Time required for lowering the pressure in the chamber from $P_i$ (initial) to $P$ is given by

$$\text{time required } t = \left( \frac{V}{S_e} \right) \ln \frac{P - \left[ 1 + \left( \frac{S_e}{C} \right) \right] P_e - \left[ 1 + \left( \frac{\text{Ps}}{P_i} \right) \right] P_i}{P - \left[ 1 + \left( \frac{S_e}{C} \right) \right] P_e - \left[ 1 + \left( \frac{\text{Ps}}{P_i} \right) \right] P_i}$$

(4)

- The total effective specific speed $S_{\text{ef}} = 2S = 3178.2$ lt/sec
- The ultimate pressure in the chamber $P_u = 6.884 \times 10^{-7}$ Torr
- Total out gassing rate $Q_d = 1.094 \times 10^{-3}$ Torr litre/sec
- Time required is $t = 68.04$ min

6. Conclusions:
A conceptual design approach of setting up HHF test facility at IPR has been discussed and highlighted the features of the vacuum chamber with the design calculations. Theoretical calculations were done to support the conceptual design and FEA structural analysis was carried out to identify the deflections and observed to be in the safe limit. Through radiation analysis, the surface temperature inside the chamber is determined which gives an outline for the cooling of the chamber.

7. References:
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[6] ASME Boiler and Pressure Vessel Code (BPVC): BPVC Section VIII – Rules for construction of pressure vessels Division 1.