DESIGN OF PLASMA FACING COMPONENTS FOR THE SST-1 TOKAMAK

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Abstract

Steady state Superconducting Tokamak, SST-1, is a medium sized tokamak with major and minor radii of 1.10 m and 0.20 m respectively. Elongated plasma operation with double null poloidal divertor is planned with a maximum input power of 1 MW. The Plasma Facing Components (PFC) like Divertors & Baffles, Poloidal limiters and Passive stabilizers form the first material boundary around the plasma and hence receive high heat and particle fluxes. The PFC design should ensure efficient heat and particle removal during steady state tokamak operation. A closed divertor geometry is adopted to ensure high neutral pressure in the divertor region (and hence high recycling) and less impurity influx into the core plasma. A set of poloidal limiters are provided to assist break down, current ramp-up and current ramp down phases and for the protection of the in-vessel components. Two pairs of Passive stabilizers, one on the inboard and the other on the outboard side of the plasma, are provided to slow down the vertical instability growth rates of the shaped plasma column. All PFCs are actively cooled to keep the plasma facing surface temperature within the design limits. The PFCs have been shaped/profiled so that maximum steady state heat flux on the surface is less than 1 MW/m^2.

1. Introduction

A Superconducting Steady state Tokamak, SST-1, is being designed to address some of the physics and technological issues related to steady state tokamak operation. The proposed tokamak is a medium sized device with major radius of 1.10 m and minor radius of 0.20 m. Machine parameters of SST-1 are given in Table 1. Elongated plasma operation with double null poloidal divertor and a maximum steady state input power of 1 MW is planned. Plasma facing components of SST-1, comprising of Divertors & Baffles, Poloidal limiters and Passive stabilizers are to be designed to accommodate the envelope of equilibria defined by elongation, κ = 1.7 to 1.9, triangularity, δ = 0.4 to 0.7 and plasma internal inductance, l_i = 0.75 to 1.40. In long pulse (quasi-steady state) discharges, like the one in SST1, the design of plasma facing components have to ensure steady state heat removal capability. Particle removal in steady state is also a major concern. The latter requires the divertor to be compatible with high pumping speed requirement.

TABLE 1. BASIC MACHINE PARAMETERS OF SST-1

Major radius, R_o	=	1.10 m
Minor radius, a	=	0.20 m
Elongation, κ	=	1.7-1.9
Triangularity, δ	=	0.4-0.7
Internal inductance, l_i	=	0.75-1.40
Toroidal field at R_o , B_0	=	3 T
Plasma current, I_p	=	220 kA
Pulse duration	~	1000 s
Plasma species		Hydrogen and Limited Deuterium
Configuration		Elongated/D-shaped, SN/DN divertor Plasma

The poloidal limiter, divertor, and passive stabilizer in SST-1 are actively cooled so as to keep the surface temperature of the plasma facing components less than 1000°C. In the present design, the steady state heat removal capability is limited to a maximum of 1 MW/m^2 due to mechanical attachment scheme adopted for actively cooled of PFCs. The plasma facing component surfaces have been profiled/shaped so that the maximum steady state heat flux on the surface is less than 1 MW/m^2. The PFCs are designed for baking at 350°C.

The plasma facing components will be experiencing large electromagnetic forces during VDEs and disruptions due to induced eddy currents and also due to halo currents. The PFCs and their support structure have to be designed to handle these large electromagnetic loads. At the same time the supports have to be flexible enough to keep thermal stresses within acceptable limits during baking and/or during steady state operation. The support structure is being designed to meet these conflicting requirements. Here we discuss the requirements and the design adopted to meet these requirements on the plasma facing components for steady state operation.

2. Design requirements

2.1. Operational and configurational requirements

Divertors are to be designed for worst possible heat load when 80% of input power is conducted across the separatrix. The inboard and outboard divertors are designed to receive 0.15 MW and 0.35 MW of power respectively. The divertor geometry should be such that neutral pressure in the divertor region should be high for efficient pumping of the divertor region and reduction of electron temperature due to high recycling. A closed divertor geometry will be the ideal choice where the recycled particles are directed away from the plasma. To ensure a closed divertor configuration a set of baffles are required.

A set of poloidal limiters are required to assist the plasma breakdown, current ramp-up and current ramp-down and for the protection of RF antennae and other in-vessel components during steady state operation and during VDEs and disruption. The outboard limiter is to be made movable to offer effective protection to the antennae that are movable. The inboard and outboard set of limiters are to be designed to take about 4% of the input power during steady state operation and up to 50% of the input power during plasma current ramp-up and ramp-down phases (up to about 4 seconds) and during short duration circular plasma operation (in the initial phase of SST-1 operation).

A set of passive stabilizers are required for SST-1 to slow down the vertical instability growth rate to ensure the feasibility of active feedback control of the vertical instability. The passive stabilizers are toroidally continuous and in saddle configuration forming a conducting shell around the plasma. The passive stabilizer should be made of high electrical conductivity material (≥93%IACS) and possess good mechanical properties to withstand electro-magnetic forces generated during VDEs and disruptions due to induced currents.

Plasma facing surfaces of the PFCs are to be kept below 1000°C during steady state operation. The stabilizer plates are to be kept below 150°C to ensure good electrical conductivity of the material. Hence active cooling of PFCs are essential. The PFCs may need to be baked up to 350°C for about 48-72 hours to reduce impurities into the plasma and to have good density control. The systems are to be designed to satisfy this requirement. The plasma facing components will be experiencing large electro-magnetic forces during VDEs and disruptions due to induced eddy currents and due to halo currents. The PFCs and their supports have to be designed to handle such high electro-magnetic loads. At the same time the supports have to be flexible enough to keep thermal stresses within acceptable limits during baking and/or during steady state operation. The PFC designs should be modular for easy maneuverability and maintenance inside the vessel and should offer enough flexibility to align the components with respect to the magnetic fields. The module joints of passive stabilizers should ensure the required electrical conductivity for passive stabilization.

2.2. Requirements onm materials

Very high thermal conductivity and good thermo-mechanical properties etc. are essential requirements for candidate materials of SST-1 plasma facing armor material. Since tolerance level of low-Z impurities in plasma is significantly higher than for high-Z impurities, low-Z material like Beryllium or Carbon based materials are preferred over high-Z materials like Tungsten or Molybdenum as the armor material. Though Beryllium has certain advantages over Carbon based materials, Carbon based materials are chosen as PFC-armor due to their wide operational experience and due to non toxicity. Isostatically pressed fine grained graphite will be the base line armor material for PFCs of SST-1 tokamak.

Good thermal conductivity and good mechanical behavior at elevated temperatures and after exposure to high temperatures for long duration is required for actively cooled substrate of divertor and limiter assemblies. In addition to the above properties passive stabilizer material requires high electrical conductivity at elevated temperatures. Copper based alloys like Copper-Zirconium or Copper-Chromium-Zirconium will be the most suitable materials because of their good electrical and thermal conductivities and good thermo-mechanical properties and relatively less degradation of mechanical properties after exposure to high temperatures for long duration. Stainless steel (SS-304) and to a certain extent Inconel are the baseline materials for PFC support structure and fasteners.

3. Design description

3.1. Divertor & baffle

The elevation view of divertors along with other PFCs are shown in Figure 1. The inboard and outboard divertor plates are designed for the worst possible heat loads by assuming in-out asymmetry of 1:2 (SN) for the inboard divertor and 1:4 (DN) asymmetry for outboard divertor. The up-down

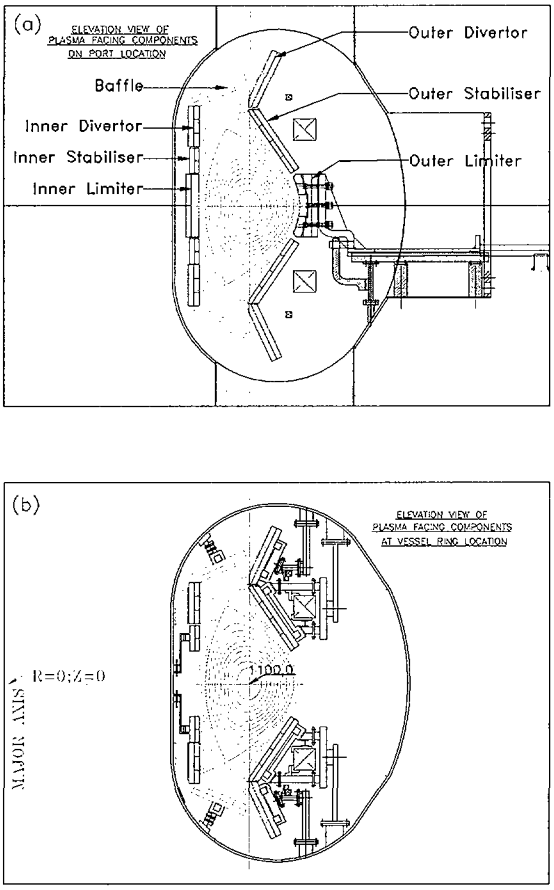

FIG. 1. Elevation view of the Plasma facing components (a) at the port location with limiter supports and (b) at the vessel ring location with supports of divertor and passive stabilizers.

asymmetry of 1:1.2 has been assumed for taking into account the relatively higher power loads on the divertor plates facing the ∇B drift direction for ions. The normal incident peak heat flux (calculated by assuming SOL width of 5 mm for heat flux, λ_q, at the outboard mid-plane) on inboard and outboard strike point is 1.6 MW/m^2 and 5.6 MW/m^2 respectively. The poloidal inclination of the outboard divertor plates is adjusted so as to have the heat flux averaged over 50 mm poloidal length (typical width of a graphite tile) at the strike point to be less than 0.75 MW/m^2. However, the inboard divertor is not inclined to the optimum requirements but are kept parallel to the vacuum vessel due to space constraints. Still, the average heat flux is in the tolerable limits. The target points of inboard as well as outboard divertor plates have been chosen at a distance as large as practicable from the null point. This reduces the electron temperature at the target plate and decreases the impurity influx from divertor region into the core plasma region. A baffle has been incorporated in the design so as to form a closed divertor configuration, which helps in increasing the neutral pressure in the divertor region thus improving the neutral particle recycling. The baffle is designed assuming an average heat flux of about 0.6 MW/m^2.

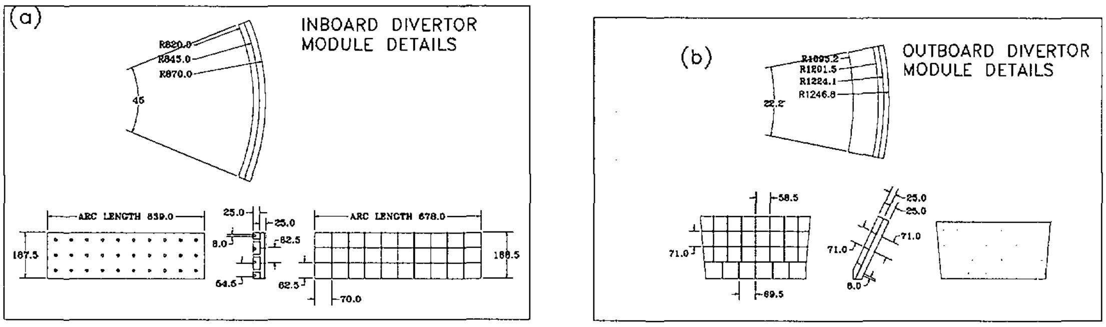

FIG. 2. Module dimension Details of (a) inboard divertor and (b) outboard divertor.

In the proposed design, the divertor assembly consists of graphite tiles mechanically mounted on a 25 mm thick back plate made up of copper alloy with a 0.2 to 0.5 mm thick flexible graphite foil used as a compliant layer for improving the contact conductance. The inner and outer divertors are in modular form for easy handling. The inner one consists of 8 modules each on top and bottom and the outer one consists of 16 each on top and bottom. The dimensions of the modules are shown in Figure 2. The top and bottom baffles consist of 8 modules each.

3.2. Poloidal limiter

There are two outboard limiters placed 180° apart (on port numbers 3 and 11) and two inboard limiters are placed at the same toroidal location.

A set of limiters to accommodate various plasma equilibrium configurations, from circular to highly D-shaped plasmas, is designed. The plasma configuration with $\kappa=1.8$ and $l_i=1.4$ is taken as the reference equilibrium for the outboard poloidal limiter design. On the inboard side, a safety limiter is placed 30 mm away from the separatrix. The front face of the limiter is flush with inner passive stabilizers and divertors. The height of the set of limiters is restricted to ±0.145 m, so as to fill the vertical opening between the top and bottom passive stabilizers, and to allow thermal expansion and other required clearances. The horizon of the outboard poloidal limiter plasma facing surface conforms to a circular arc of radius 0.30 m centered at the major radius of 1.03 m on the midplane up to a height of ± 0.125 m. From ± 0.125 m to ± 0.145 m vertically, appropriate poloidal curvature is made to avoid interference with divertor operation at high κ and l_i equilibria. For the reference equilibrium, the front edge of the limiter closely approximates the +3 cm flux surface. For this configuration, a peak heat load of 6.4 MW/m^2 is expected for normal incidence. As we limit the steady state heat removal capability to less than 1 MW/m^2, the limiter surface is shaped/profiled in the toroidal direction. We opted for a semicircular shape with the front edge having a radius of curvature of 1.095 m in the toroidal direction. The toroidal width of the limiter is 0.37 m with appropriate curvature at the ends. Figure 3.(a) shows the outboard limiter dimensions.

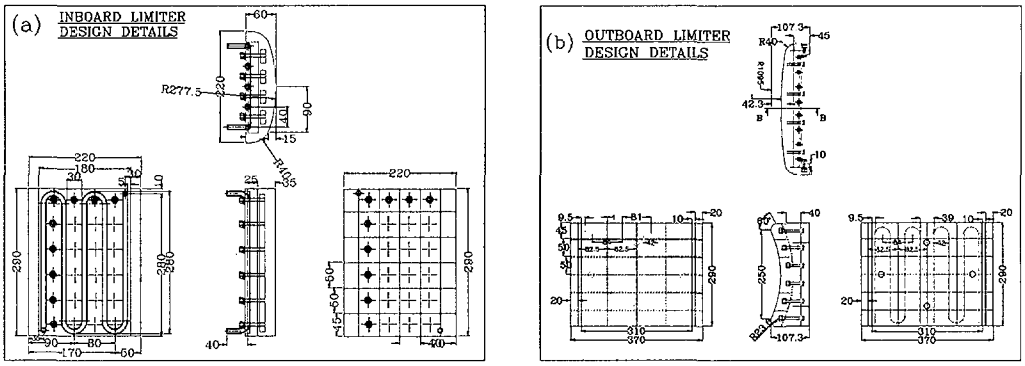

FIG. 3. Design details of (a) Inboard limiter and (b) Outboard limiter.

For the inboard limiter also, the peak heat load for normal incidence is estimated to be 6.4 MW/m^2. To reduce the heat flux to less than 1 MW/m^2, this limiter is also toroidally profiled. As mentioned above, a semicircular shape with the front curvature of 0.278 m in the toroidal direction has been adopted. The toroidal width of the inboard limiter is 0.22 m with optimum curvature at the edges. The design details are shown in Figure 3.(b).

3.3. Passive stabilizers

There are two pairs of stabilizers one on the inboard and the other on the outboard side of the plasma, placed above and below the midplane. At one toroidal location the top and bottom plates are connected with current bridges to make a saddle configuration. The heat loads during normal operation on the stabilizers are very low. However, the passive stabilizers have been designed to accommodate heat flux up to 0.25 MW/m^2. On 25 mm thick copper alloy stabilizer plate, 20 mm thick graphite tiles of suitable dimensions will be mechanically attached with 0.2 mm flexible graphite compliant layer. With the active cooling, the plate temperature will be about 150°C and the graphite surface will be below 300°C.

The passive stabilizers will be made by joining a number of modules *in-situ* with very low contact resistance (mechanical) joints. Each of the inner top & bottom stabilizer will consist of 8 modules, weighing about 20 kg each. Each of the outer top & bottom stabilizers will be made of 16 modules, weighing about 45 kg each. Figure 4 shows the dimensions of the inboard and outboard stabilizer modules.

The inner and the outer current bridges will be of ‘Radial Lap’ type with appropriate geometry and cross-sections of the vertical straps to withstand the forces and meeting the least possible resistance in the saddle path and to minimize the error fields. To prevent flow of induced toroidal currents in stabilizer loops through the supports, during VDEs and disruptions, the support structures of stabilizers are electrically insulated from the vacuum vessel and shunt resistances of appropriate values are provided across the electrical breaks and across the current bridges.

3.4. Cooling and baking of PFCs

All PFCs are cooled and baked by channels embedded in the copper-alloy back plates. De-ionized water at about 35°C will be used for cooling of the PFCs and Nitrogen gas at about 400°C will be used for baking. All PFC modules, except Outboard limiter will have one micro-circuit each. The outboard limiter will have two microcircuits, to optimize the flow parameters. Initial flow parameters for cooling is arrived through analytical calculations. Since the same channels are being used for cooling and baking, the compatibility of the layout for both is checked and the channel layout is finalized suiting the requirement of the each subsystem for baking and cooling. The flow parameters thus

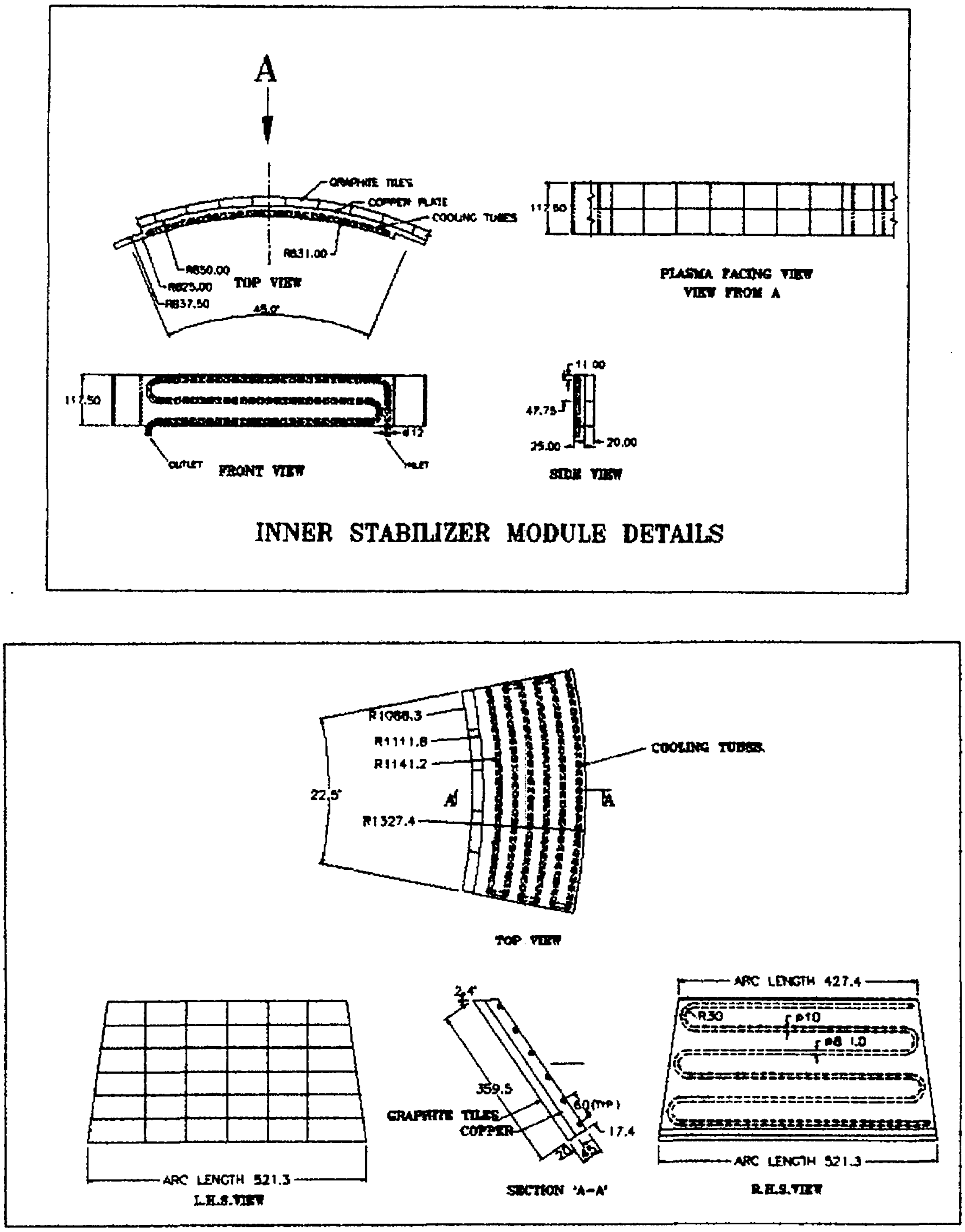

FIG. 4. Module dimension details of (a) Inboard and (b) Outboard passive stabilizer.

derived are used in finite element calculations to check the temperatures of various materials in steady state and transient events. Finite element analysis is carried out using ANSYS®, assuming the worst case scenarios for each component. Figure 5.(a) shows finite analysis results for a typical case of inboard divertor plate where the heat flux is falling exponentially and Figure 5.(b) shows a typical case with uniform heat flux of 0.25 MW/m^2 on the passive plates. The flow parameters for SST-1 plasma facing components are shown in table 2 and table 3.

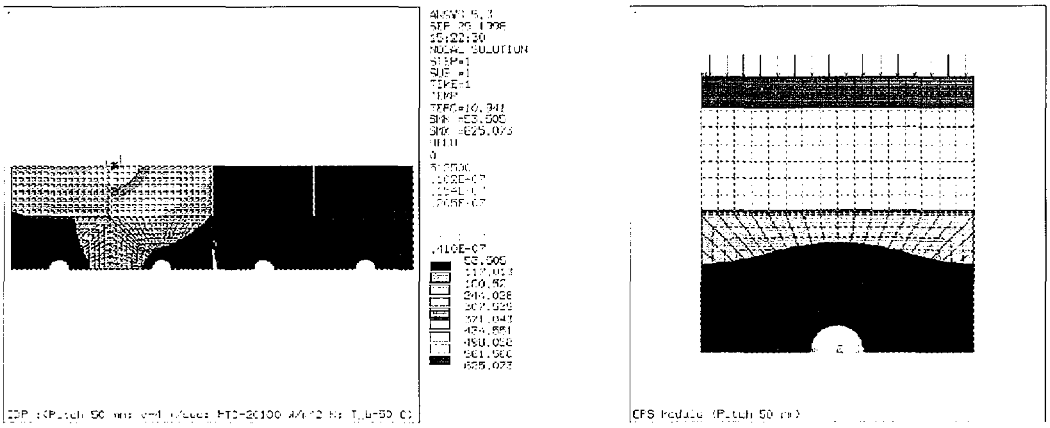

FIG. 5. Finite element analysis for (a) exponential heat flux profile as in divertor and (b) uniform heat flux of 0.25 MW/m^2 as in passive plates.

TABLE 2. COOLING PARAMETERS OF THE PFCs

	IDP	*ODP*	*IPS*	*OPS*	*IL*	*OL*
Diameter (mm)	10	10	10	10	8	8
Mass flow rate (kg/s)	0.310	0.310	0.271	0.271	0.223	0.223
Velocity (m/s)	4	4	3.5	3.5	4.5	4.5
Heat tranf. coeff. (W/m^2)	20,000	20,000	18,000	18,000	22,000	22,000
In-out temperature (°C)	35/85	35/85	35/85	35/85	35/85	35/75
Pressure drop (bar)	1.81	1.92	1.21	1.75	1.96	1.30
Cu plate surf. temp. (°C)	164	194	110	116	152	206
Compl. Layer temp. (°C)	172	342	172	178	158	443
Graphite surf. temp. (°C)	641	766	241	248	846	881

TABLE 3. BAKING PARAMETERS OF THE PFCs

	IDP	*ODP*	*IPS*	*OPS*	*IL*	*OL*
Diameter (mm)	10	10	10	10	8	8
Mass flow rate ($\times 10^{-3}$ kg/s)	5.27	3.91	6.52	7.13	6.93	7.54
Velocity (m/s)	40	30	32	35	34	37
Heat tranf. coeff. (W/m^2)	413	342	332	380	369	390
Out temperature (°C)	361	364	359	352	353	356
Pressure drop (bar)	0.48	0.23	0.30	0.52	0.43	0.47
Graphite surf. temp. (°C)	350	350	350	350	350	350

3.5. Tile design and mounting

One of the major constraints of PFC design is the tile attachment scheme. Though graphite tiles that are brazed to copper back plate are preferred for high heat transfer, we opted for mechanically attached tile system in the initial phase of operation. Hence heat removal capability is limited to less than 1 MW/m^2. The design adopted for the PFCs is shown in Figure 6 with typical dimensions. Mechanical stress analysis is carried out using ANSYS®. A more detailed thermo-mechanical analysis is underway. Initial analysis shows that the design can be used for heat fluxes up to about 1 MW/m^2. For Inner and outer divertors 25 mm thick graphite tile is bolted to actively cooled copper back plate with 0.5 mm thick flexible graphite compliant layer. In the case of limiter, the tile thickness varies from

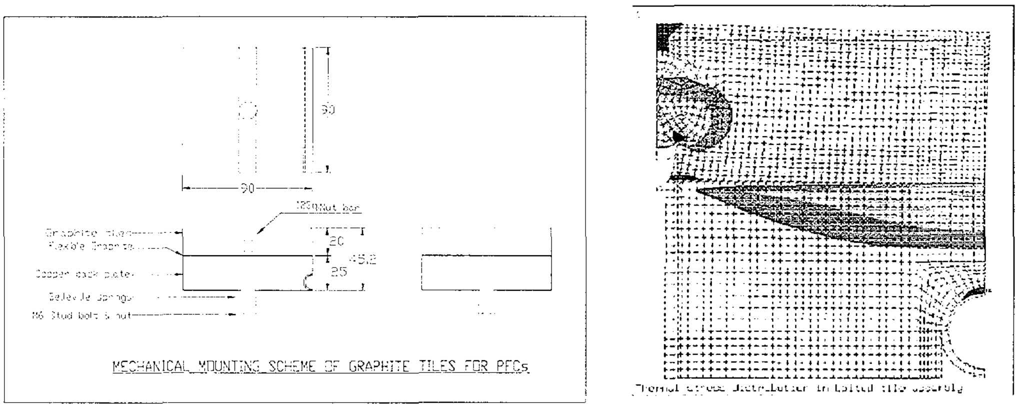

FIG. 6. (a) Tile attachment scheme of PFCs with typical dimensions. (b) Finite element analysis result showing the thermal stresses with bolting.

40 to 22 mm, as it is profiled toroidally. Passive plates are covered by 20 mm graphite tiles. The design ensures graphite surface temperature to be less than 1000°C.

3.6. Forces on the PFCs

SST-1 tokamak will operate plasmas of D-shaped cross-section and such plasmas are inherently unstable for motion in vertical direction. Because of good inductive coupling of the PFCs with the plasma, the movements of the plasma or the alterations in the plasma current cause eddy currents to be induced in these structures. Interaction of these currents and fields generates significant electro-magnetic loads on the PFCs. Additional forces arise from the development of the '*halo*' plasma. This forms when the shifted plasma has physically touched the metallic structures like divertor or baffle, with a concomitant decay in plasma current. The halo plasma causes halo currents to flow poloidally in the PFCs and vessel and leads to additional forces. The loads on the PFCs have been calculated for these events. A typical scenario modeled is an upward VDE up to Zp=0.25 m, followed by disruption of full plasma current in 1 ms. The plasma position and current are given an ad-hoc but typical wave form for calculating eddy currents. The loads are calculated using a finite element code, EFFI, where the PFCs are modeled as toroidal filaments with appropriate cross-section. There are large forces on passive stabilizers due to toroidal eddy currents. The outboard divertors and baffles do not form a toroidal loop and there is shielding of the PFCs from the inner vessel post. The worst-case halo current forces have been estimated by assuming 0.4 times plasma current with a toroidal peaking factor of 2 on the halo current, and the halo current traversing the full poloidal length of the PFCs.

3.7. PFC support structure

The support structures of divertors and passive stabilizers are designed as per the requirements of modularity of the components for easy handling during assembly and disassembly of modules inside the vacuum vessel within the limited space. The supports are also designed to withstand the static (dead) weights of the PFCs and impulsive electromagnetic forces during VDEs, disruptions and due to halo currents. The supports are designed to allow thermal expansion of the components (by deflecting the support structure elements) during baking to limit thermal stresses within acceptable limits. Differential thermal expansions of the vessel, the PFCs and the support itself, during baking and during normal (steady state) operation are taken care of in the design. The elevation view of supports of Divertors and Passive stabilizers is shown in Figure 1.(a). The Outboard limiter is mounted on a movable support structure attached on radial port with suitable vacuum interfaces.

4. Conclusion

The design of the plasma facing components for the SST-1 tokamak is completed. The steady state operational requirements put stringent constraints on materials, heat removal systems and the design options. Carbon based materials are chosen as plasma facing material while copper based alloys are opted for the heat sinks as well as passive stabilizers. Thermal hydraulic calculations were done which gave reasonable flow parameters ensuring the design requirements on the surface temperatures of PFCs. The design of the divertor and baffle ensures the maximum heat flux is less than 1 MW/m^2 and provides a closed divertor configuration. This in turn enhances the neutral pressure and increases recycling. The limiters are designed to protect the RF antennae and at the same time to assist the various start-up scenarios. The design of the passive stabilizers ensures the feasibility of active feedback control of the vertical instability by slowing down the growth rates. The engineering design of various PFCs and their supports is currently underway.