THERMAL-HYDRAULICS AND STRUCTURAL ANALYSES OF LLCB TBM SET

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Abstract

Indian Lead-Lithium cooled Ceramic Breeder (LLCB) Test Blanket Module (TBM) is one of the tritium breeding blanket concepts being developed for testing in ITER. The paper discuses about the conceptual design and analysis work related to some of the key components of LLCB TBM set. First wall (FW) is a plasma facing component of the TBM which is designed to withstand high heat flux from plasma. FW is cooled by high pressure, high temperature helium gas flowing through coolant channels. The detailed thermal–hydraulics of FW has been performed based on the heat flux and neutronic heat generation. ANSYS CFX has been used for CFD analysis. The distribution of flow in different flow circuits of FW from manifolds has been performed and the flow distribution is found to be uniform in all the circuits. Thermal-hydraulic analysis of helium flow inside the FW channels and manifolds to estimate temperature, pressure drop and heat transfer coefficient has been discussed in the paper. TBM shield is located behind TBM to provide shielding from high energy neutrons to magnets and other components behind the TBM set. Water flows in parallel channels inside TBM Shield, provides the function of neutron moderator as well as coolant to remove heat deposited by the neutrons in the structure. Flow rate in parallel channels of shield has been regulated using orifice of different diameter. CFD Flow analysis inside shield has been performed to validate the distribution of flow inside the parallel channels. Based on velocities obtained, the heat transfer coefficient have been evaluated and thermal analysis of TBM shield has been performed considering thermal load from neutronic heat generation. The results obtained from thermal–hydraulic analysis of FW, manifolds and TBM shield have been used for thermo-structural analysis of LLCB TBM set based on load combinations as per ITER load specifications. RCC-MR 2007 code has been used for the structural assessment and prevention of p-type and s-type damages. The temperature and stresses are found to be within the acceptable limits and safety margins.

1 Introduction

Testing of blankets which are used for insitu tritium breeding and nuclear heat extraction are one of the objectives of ITER [1]. Many different concepts are being developed worldwide for tritium breeding test blanket modules. India is working on one such concept known as LLCB (Lead lithium ceramic breeder) TBM (Test blanket module) [2].Indian LLCB TBM set consists of LLCB TBM, TBM shield, supports, piping and flange as shown in Fig. 1(a). It is cantilevered to TBM shield behind using a support structure which in turn is cantilevered to port using a bolted flange. A U-shaped helium cooled First Wall (FW) along with top, bottom and back plates encloses the internal components of LLCB TBM. The TBM internals consist of four ceramic breeder canisters (Li_2TiO_3) in the form of pebble bed with molten Pb-Li flowing around these canisters to cool the ceramic breeders and the internal structure. India specific steel known as IN-RAFMS (Reduced Activation Ferritic Martensitic Steel) [3] is the structural material for LLCB TBM.

TBM Shield made of SS 316 L (N)-IG is located behind the TBM. It has 50:50 ratio by volume of steel and water to shield neutrons as well as to provide cooling. It consists of two symmetrical parts that have grooves to accommodate and route pipes to the TBM. In each half, water enters at the top manifold and flows down through 12 parallel channels as shown in fig. 1(b) and finally gets collected at the bottom manifold and exits from the TBM shield as shown in Fig 1(c). The neutronic heat generated inside shield structure is extracted by flowing water inside channels. Indian LLCB TBM set has been designed as per ITER loads and operating conditions. The conceptual design and related analysis of LLCB TBM set has been completed in April 2017. The thermal analysis of TBM internal components and FW for steady state and transient operation scenarios based on analytically calculated Heat Transfer Coefficients (HTC) is discussed in [4]. The thermal, electromagnetic, seismic analysis and the load combination structural analysis of TBM set based on ITER load combination criteria has been discussed in [5].

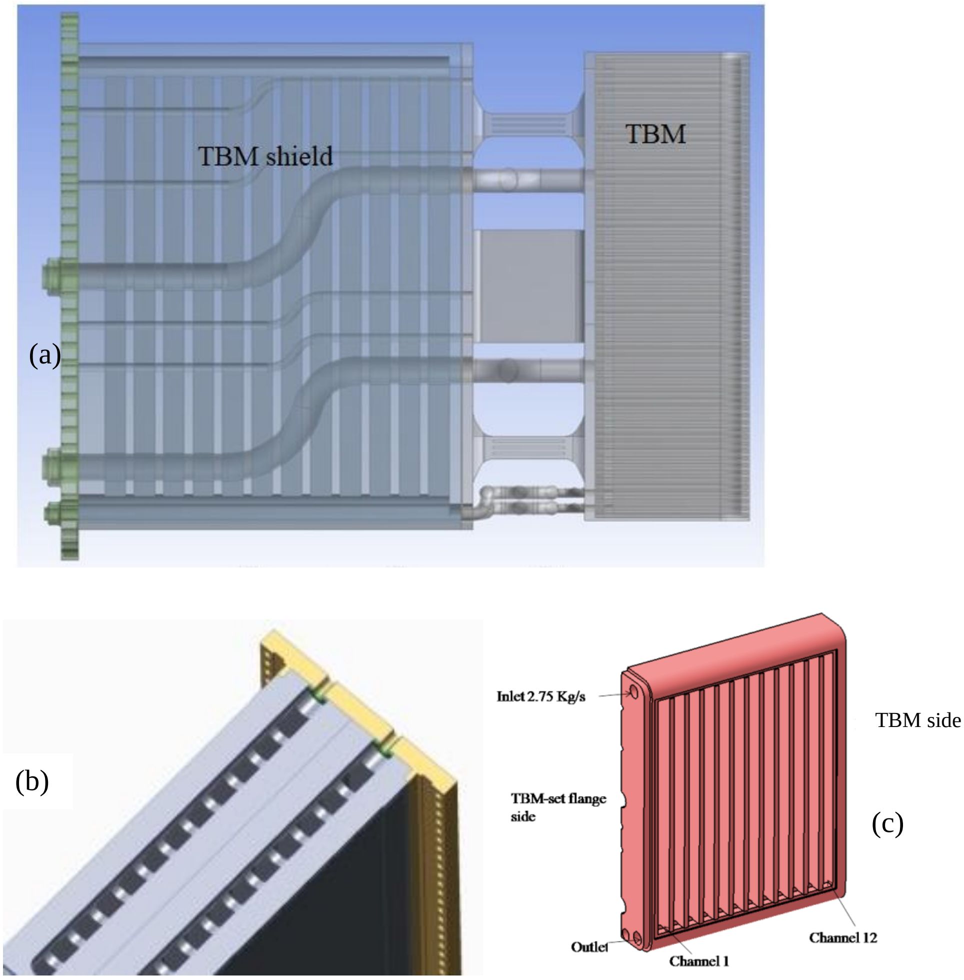

FIG. 1 a) LLCB TBM set b) Inlet manifolds in shield and c) water flow arrangement in one half of TBM shield

The present paper primarily focuses on detailed thermal hydraulics of FW, its manifolds and TBM shield using CFD software ANSYS CFX [6] and their structural analysis using ANSYS workbench mechanical [6]. In FW thermo-hydraulic analysis, flow distribution analysis has been performed to determine the flow rate distribution from FW manifolds and their uniformity in each FW circuit. Afterwards, an analysis with a single FW circuit has been performed to estimate the temperature distribution and validate the CFD calculated pressure drop and HTC with analytical correlations. CFD analysis of flow distribution in TBM shield and its thermal analysis has been discussed. Structural analysis of these components of TBM set has also been discussed in the paper.

2 Thermal-hydraulics of TBM First wall and manifolds

The conceptual design of FW of LLCB TBM has 13 parallel coolant (helium) flow circuits [7]. Each circuit consists of a 5 pass serpentine flow arrangement and hence in total, there are 65 coolant channels in FW. The channel have cross section of 20x20 mm with 3mm fillet at the corners. The helium inlet temperature and pressure is 300 °C and 8 MPa respectively. The total inlet mass flow is 1.6 kg/s which correspond to a velocity of ~50 m/s in all the flow circuits. FW is designed to withstand a heat flux of 0.3 MW/m^2 [4] and the deposited neutronic heat [8].

2.1 **Flow distribution in FW parallel circuits from manifolds**

A hydraulic analysis has been performed to estimate the flow distribution from manifolds into each circuit of FW. The model consists of all the 65 channels (13 circuits) which are connected to the manifold. Here, only

fluid domain has been modelled for the hydraulic analysis to estimate the flow distribution, velocities and pressure drop in the helium cooling circuits and the manifold. Inlet mass flow rate of 1.6 kg/s and outlet pressure of 0 Pa has been considered as inputs for this analysis. K-epsilon turbulence model has been used since it is most widely accepted model and does not require very fine mesh near the boundary walls.
The velocity distribution plot is shown in Fig.2.The plot shows the distribution of flow from inlet manifold on left side into the thirteen parallel circuits of five passes and similarly collection of flow from these circuits into outlet manifold on right side. The plot shows the max velocity of 117 m/s at 180° bends of the FW channels. Elsewhere inside the channels, the velocity is ~50 m/s. The pressure plot is shown in Fig. 3.The total pressure drop (from inlet to outlet pipe) is 0.18 MPa. Pressure drop in each circuit is around 0.14 MPa and rest 0.04 MPa is in the manifolds.

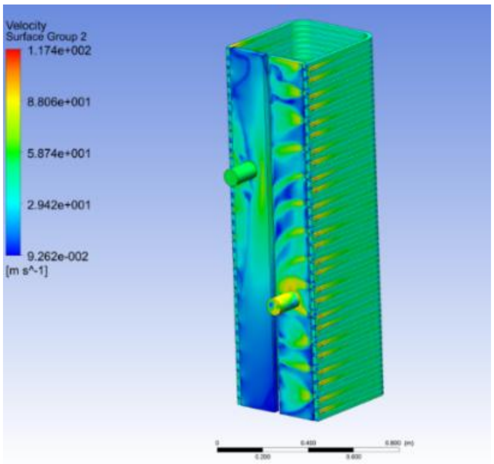

FIG. 2 Velocity plot

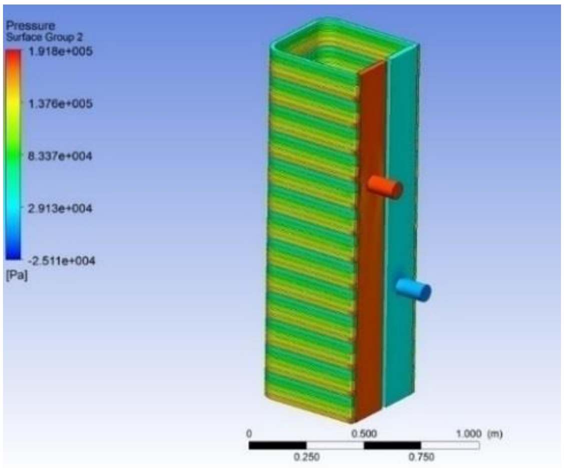

FIG.3 Pressure plot

The mass flow rate in each circuit has been calculated in ANSYS CFX. If 1.6 kg/s is to be distributed equally in each of the 13 circuits, the required mass flow rate in each circuit is 0.125 kg/s which corresponds to 50 m/s. The mass flow rate distribution calculated using ANSYS CFX is shown in Fig. 4 which shows that flow within the first wall circuits is uniform with 2.2 % deviation from maximum value.

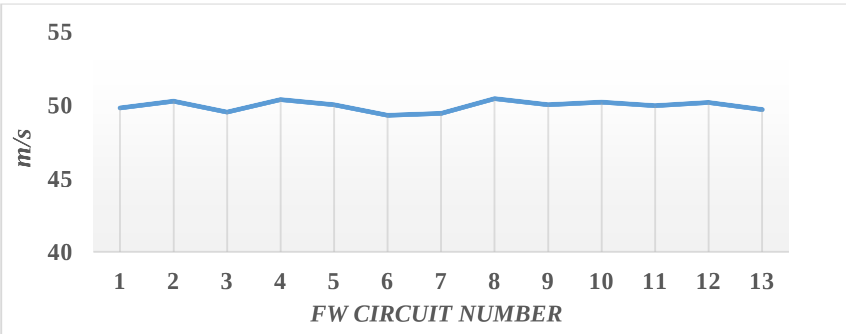

FIG. 4 Flow velocity in parallel FW circuits

2.2 **Thermal –hydraulic analysis of single FW circuit**

As all the 13 circuits in the FW are in parallel and repetitive in nature, a detailed thermo-hydraulics on a single FW circuit is sufficient to estimate the temperature, HTC, pressure drop etc. In this analysis the fluid flow and temperature of the FW has been analyzed in one such circuit. Inlet velocity of 50m/s, outlet pressure of 0 Pa along with surface heat flux and neutronic heat loads has been considered as inputs for this analysis. K-epsilon turbulence model has been considered.
The velocity streamline plot in the FW cooling channel is shown in Fig.5. Except at the bends the velocity is same as inlet velocity value of ~ 50 m/s. The high velocity regions are at locations of 180° bends. The pressure difference between inlet and outlet is calculated from pressure profile shown in Fig.6. The pressure drop obtained in CFX is 0.14MPa between inlet to outlet which is same as discussed in section 2.1. Analytically, the pressure drop of 1.44 bar has also been calculated considering pressure drop due to bends and frictional pressure drop in straight channels using the formulas given in [9]. The temperature distribution of FW obtained shown in

Fig. 7. The maximum temperature on the FW is 481 °C. The FW temperature obtained from thermal analysis in [4] is 473.4 °C, which differs less than 2 % from this analysis. Fig. 8 shows the channel wall temperature.

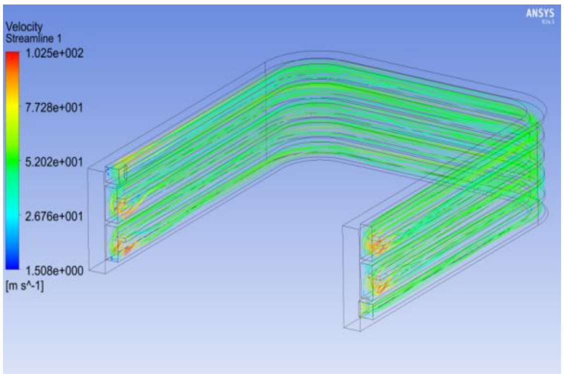

FIG. 5 Velocity streamlines in the FW cooling channel

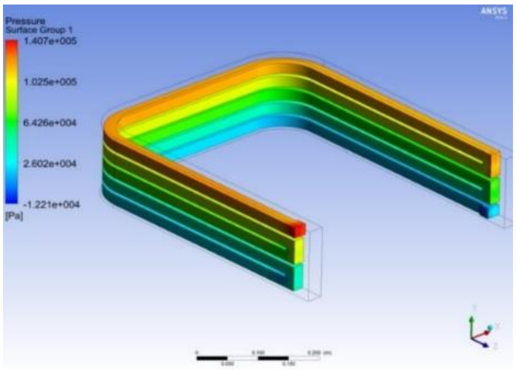

FIG. 6 Pressure profile in FW

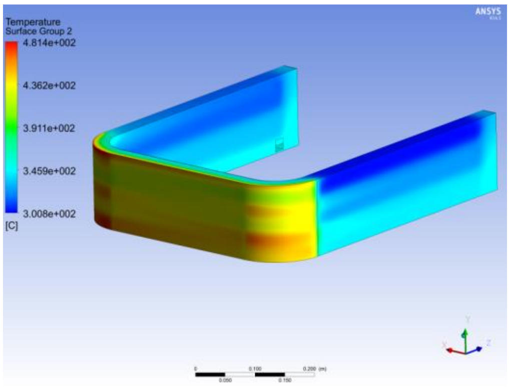

FIG. 7 Temperature profile in FW

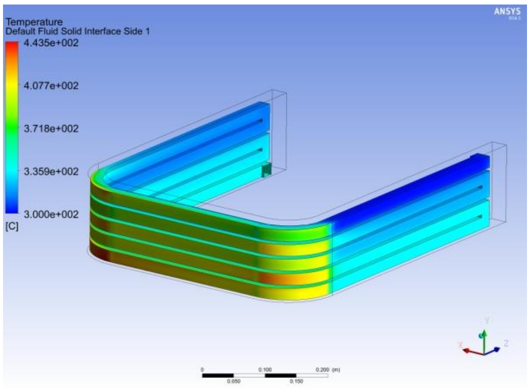

FIG. 8 Channel wall temperature of FW

The calculation of HTC has been shown in table 1 using the basic heat transfer convection equation: HTC = Q/ $(T_w - T_b)$, where, Q is the heat flux load in W/m^2.

Table 1. Calculation of HTC from CFX

Average channel wall temperature T_w[°C]	Average Wall Heat Flux on helium channels (W/m^2) [Q]	Bulk temperature of Helium (T_b) [°C]	HTC [W/m^2-°K]
337.67	50287	323	3623

The comparison of HTC, outlet temperature of helium and pressure drop obtained from CFX and analytical calculation is tabulated in table 2. It shows the results are in good agreement. Analytically HTC has been calculated using Gnielinski's correlation from [10].

Table 2. Comparison of different parameters obtained from CFX and analytical analysis

Parameter	CFX results	Analytical results
HTC (W/m^2-K)	3623	3691
Outlet Temperature (°C)	341	340
Pressure drop (bar)	1.4	1.44

2.3 Thermal –hydraulics of FW manifolds

CFD analysis of helium flowing in manifolds has been performed to estimate HTC values in the manifolds which can be used for further for thermal analysis of TBM set. Manifold along with 13 channel entry/exits have been modeled as shown in Fig. 10 (a) for this analysis. For inlet manifold analysis, the mass flow rate has been applied at the inlet of the manifold. The same mass flow exits through the 13 channels. For Outlet manifold, the flow is reversed; the manifold receives helium from 13 inlet channels.

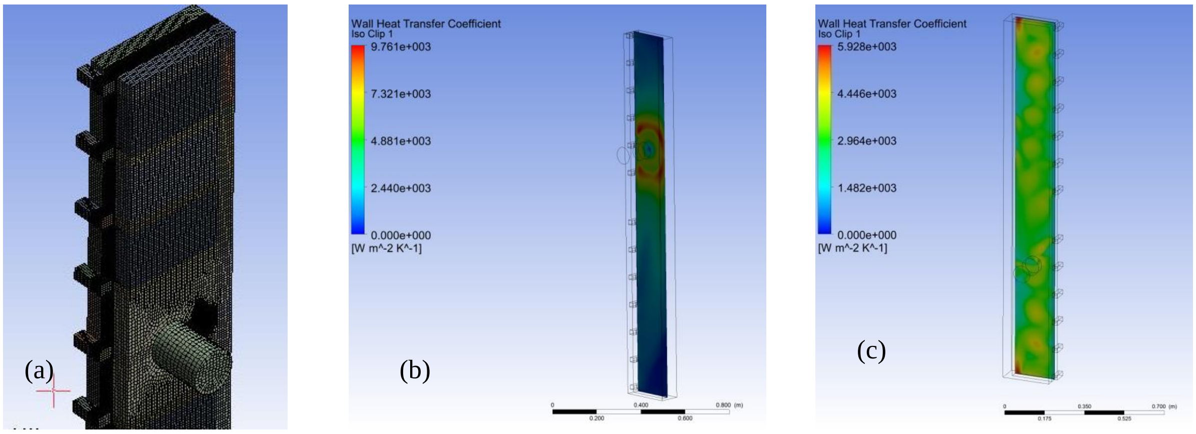

*FIG. 10(a) M*odel for helium manifolds, *(b) HTC plot for inlet manifold, (c) HTC plot for outlet manifold*

The HTC for helium in contact with inner back plate for inlet and outlet manifold is shown in Fig. 10(b) and 10(c) respectively. The average HTC as calculated on the inner BP surface was found to be 2869 W/m^{2}K and 3095 W/m^{2}K for inlet and outlet manifold respectively. As a conservative approach, the HTC value of 2000 W/m^2-K with bulk temperature of 300 °C for inlet and 340 °C for outlet manifold has been considered for the thermal analysis because of non-uniform distribution of HTC in manifolds and as most of the regions have HTC above 2000 W/m$^{2°}$K.

3 Thermal hydraulics of TBM shield

The TBM shield is made of SS 316L (N)-IG and cooled by water at inlet pressure and temperature of 4 MPa and 70 °C respectively [5]. The volume ratio of SS and water in the TBM shield is 50:50. TBM shield is made up of two symmetric water cooled sections. The flow rate in first channel near the TBM set flange has to be increased to reduce the thermal gradient between the assemblies (TBM set flange and frame) as the flange temperature will be increased by the process pipes carrying hot fluids which are welded to the flange. Flow resistances have been added to each of channels in the form of circular orifices to regulate the flow. Pressure drop in each of the flow circuit has been calculated using analytical correlations [9] for frictional and local losses (flow division, bends, merging flows). In order to keep the same pressure drop in each channel, suitable flow resistance (orifice) is introduced. To verify the analytical calculations, the flow analysis of water inside TBM shield was performed using ANSYS CFX with required orifice as added resistance to induce the required pressure drop. The model for the analysis is shown in Fig.11. The flow domain alone is modelled since the area of interest here is the distribution of flow inside the TBM shield channels. Only one side part of fluid is modelled since the other one is connected in parallel and has the same geometry. K-epsilon turbulence model has been used for this analysis.

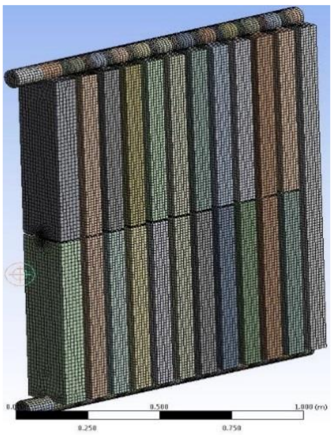

FIG. 11 Water flow model in TBM shield

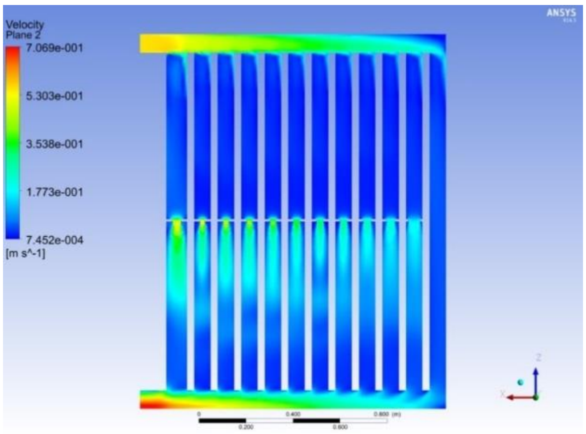

FIG. 12 Velocity plot in the mid-plane

Mid plane velocity plot showing the flow distribution in the twelve channels inside the TBM shield is shown in Fig. 12.The comparison of distribution of mass flow estimated by CFX and analytical calculation in TBM shield channels is shown in Fig. 13 which is well in agreement. The HTC has been calculated using Dittus-Boelter equation ($Nu = 0.023\ Re^{0.8}Pr^{\ 0.4}$) for turbulent flow regions. For laminar flow, Nu = 4.3 [11] has been considered.

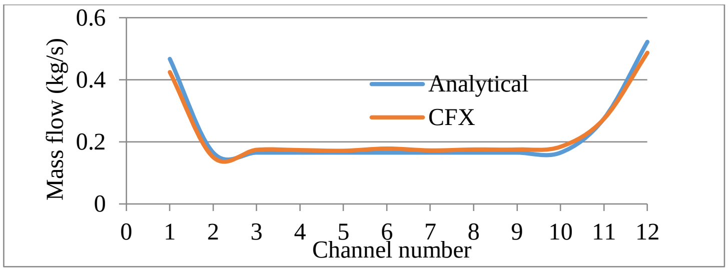

FIG. 13 Comparison between analytical and CFX calculated mass flow

The thermal analysis of TBM shield has been performed on the basis HTC calculated analytically using results from flow analysis. Radial profile contour of heat generated [8] inside the TBM shield is shown in Fig .14.The neutronic heat generation has been applied in the form of a polynomial function as a function of radial distance.

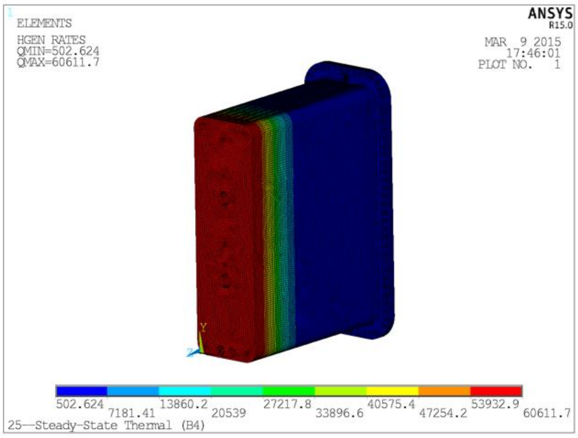

FIG.14 Heat generation plot in TBM shield

The temperature plot for full model consisting of TBM shield, TBM set flange and pipes is shown in Fig.15. The maximum temperature of TBM shield is 326 °C at the bottom of TBM shield-TBM set flange joint location near lead lithium pipes. The maximum temperature at the front side (towards TBM) of TBM shield is 120 °C. At the majority of bolt hole locations, the temperature is less than 150 °C as shown in Fig.16 which reduces thermal gradients in the bolted assembly between the port plug frame at 100 °C. The maximum temperature of 478 °C is observed on the flange at the location of helium purge outlet pipe.

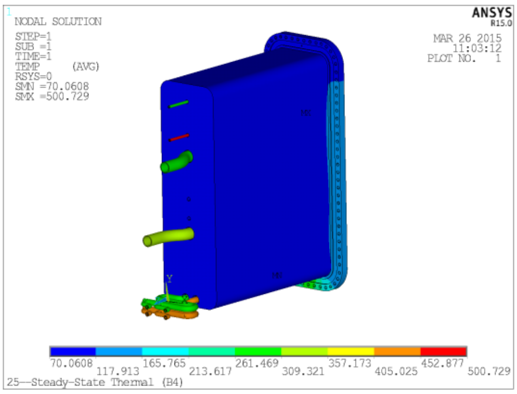

FIG.15 Temperature distribution on TBM shield

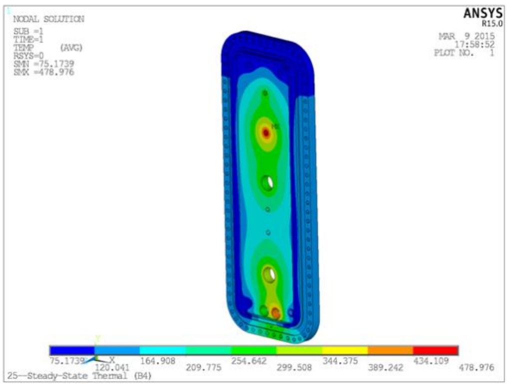

FIG.16 Temperature distribution of TBM set flange

The thermal analysis of TBM shield shows that the temperature distribution is in the range of 70 -326 °C during the normal operating conditions for the available water flow rate of 5.5 kg/s. It can be observed that the TBM shield is less than 125 °C, except at the flange side of TBM set. Further optimization will be done at a later stage to regulate the coolant flow to lower the temperatures in specific regions.

4 Structural analysis of LLCB TBM set

Structural analysis of LLCB TBM set has been performed based on relevant pressure, thermal, electromagnetic and seismic loads. Since, major design driver for FW design is pressure and differential temperature gradient from the plasma facing surface, only the analysis results for pressure and thermal loads have been discussed here. The analysis have been performed on the full TBM set and the results for FW manifolds and TBM shield have been extracted and discussed. Initially a thermal analysis is performed on the model with relevant heat transfer coefficients and then the temperature distribution is applied for thermo-structural analysis. Stress assessment for critical paths have been performed for critical and high stress regions for p type and s type damage as per RCC-MR 2007[12]. For primary loads: $P_m \leq S_m$, $P_m+P_b \leq 1.5S_m$ criteria is considered for p type damage and for primary + secondary loads Max (P_m+P_b) $+\Delta Q \leq 3S_m$ criteria is considered for s type damage where P_m, P_b, Q and S_m are primary membrane, primary bending, secondary primary +bending and allowable material stress respectively.

Maximum displacement and von mises stress for combined pressure, thermal loading is given in Fig.17 and 18 respectively. Maximum displacement is around 4.5 mm located at top and bottom corners and maximum stress is 532 MPa which is at FW manifolds location. Table 3 shows the stress assessment results at critical and high stress location in FW and manifolds. In the manifolds where the safety margins is below 1 for primary loads at the entry location of helium into FW, stiffeners have been proposed to lower the stress due to high coolant pressure (8MPa).

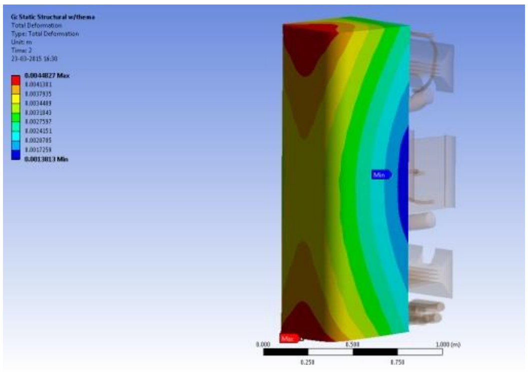

FIG. 17 Displacement plot in TBM

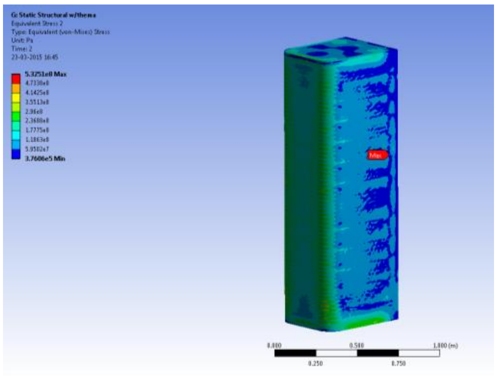

FIG. 18 von Misses Strees plot in TBM

Table 3. Stress assessments in FW and its manifolds

Location	Safety margins (p-type)		Safety margin (s-type)
	Criteria		
	P_m/S_m	$(P_m+P_b)/1.5S_m$	(Max (P_m+P_b) $+\Delta Q)/3S_m$
Manifolds highest stress region	0.56	0.72	1.14
FW front thickness	1.83	2.44	2.94
FW-bottom plate region	1.95	1.15	1.57
Manifold outer plate	15	3.95	7.13
Manifolds mid plate	2.6	3.85	Not required
Manifolds inner plate	16.2	3.9	Not required

Maximum displacement in TBM shield is 0.8 mm for pressure and thermal loads. Von Mises stress due to primary loads is shownin Fig, 19 which shows a maximum of 57 MPa. Maimum stress due to primary and secondary loads is 494 MPa which occurs locally near TBM shield-flange joint near lead lithium pipes where temperature is high. Fig. 20 shows shows the stress intensity linearization along the path in this region as P_m+P_b+Q =205 [MPa], Temperature = 120 °C, 3S_m =405 [MPa], Safety margin: 2.15.

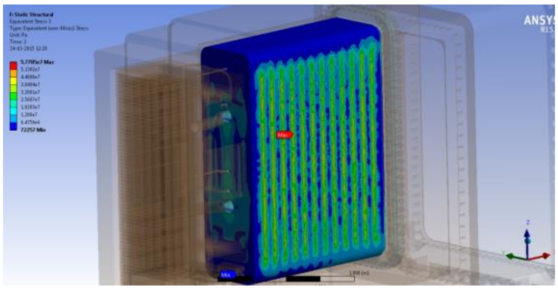

FIG.19 von mises stress plot in shield due to primary load

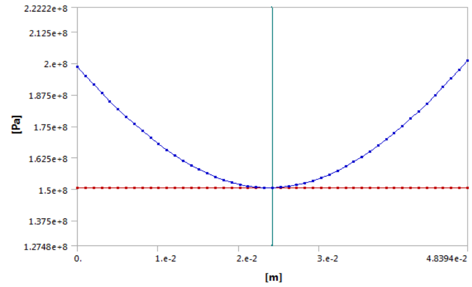

FIG.20 Stress linerization for primary and secondary loads

5 Conclusions

The flow analysis in FW and manifolds shows uniform flow in channels. Temperature and stress in FW are also within the limits. Some of the improvement in FW design have been investigated and are discussed in [7]. Temperature and stress values in TBM shield are also found to be within the acceptable limits. Further optimization in design is being performed considering fabrication feasibility. Mock-ups to validate the fabrication process and experiments to validate some of simulation results are also being planned.

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