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Design update and thermal-hydraulics of LLCB TBM first wall

Deepak Sharma[a,*], Paritosh Chaudhuri[a,b], S. Ranjithkumar[a], E. Rajendra Kumar[a]

[a] Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, 382428, India
[b] Homi Bhabha National Institute, Anushaktinagar, Mumbai, 400094, India

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ABSTRACT

The First Wall (FW) of Indian Lead Lithium Ceramic Breeder (LLCB) Test Blanket Module (TBM) is a U-shaped structure made of India specific Reduced Activation Ferritic Martensitic Steel (IN-RAFMS). As the FW is directly exposed to high heat flux from plasma, it is actively cooled by high pressure and high temperature helium gas. Following the Conceptual Design Review (CDR) at ITER, some improvement on the design of LLCB TBM has been envisaged, this includes the FW design to reduce the operational load on helium cooling process systems. The optimization studies have been carried out selecting suitable channel size, shape and no. of flow circuits of FW to keep the FW temperature and pressure drop within the acceptable limits. The parametric study has been performed with different mass flow rates and channel configurations of FW. This analysis resulted in the reduction of mass flow requirement by about 38% of the current value. The optimized parameters have been used to carry out the thermal-hydraulic and thermo-mechanical analyses of the two selected configurations of FW using ANSYS code. The temperatures and stresses are found to be within the required limits. Finally, the detailed thermal-hydraulics of final selected design of TBM FW have been performed using ANSYS CFX to estimate temperature distribution along with the validation of analytically calculated pressure drop and Heat Transfer Coefficient (HTC). It is observed that the temperature distribution on FW obtained from the flow analysis in CFX and that obtained by performing thermal analysis in ANSYS using HTC from engineering correlations are similar. The detailed analysis of the variation of HTC along the flow length of the heat flux zone has also been discussed. This paper also discusses transient and accident thermal analysis of the updated design for some of the ITER scenarios and the temperatures have been found to be within the required limits.

1. Introduction

The Indian LLCB TBM as shown in Fig. 1 uses both solid (Li_2TiO_3 ceramic pebbles) and liquid (Pb-Li eutectic) as the tritium breeder material and IN-RAFMS as the structural material. The LLCB TBM consists of U shaped First Wall (FW) with the back plate enclosing the internal components, covered by top and bottom plates. The TBM internals consist of ceramic breeder canisters (Li_2TiO_3) in the form of pebble bed with Pb-Li flowing around these canisters to cool the internal structure [1–3]. FW receives high heat flux from plasma and is actively cooled by high pressure (inlet pressure: 8 MPa), high temperature (inlet temperature: 300 C) helium flowing inside the channels, to extract the heat from incident heat flux from plasma and neutronic heat deposited on the FW structure.

After the successful completion of the CDR of LLCB TBM, some possible improvements in the design of FW are being investigated with a view to reduce the load on helium cooling process systems by reducing the mass flow requirement required to cool the FW structure. Section 2 discusses the design and parameters of the CDR configuration of LLCB TBM and the possible suitable configurations selected for parametric study. Section 2.1 discusses the different parameters and their calculation methodology required for the optimization studies. Based on the results of this parametric study, two suitable configurations and their flow parameters are discussed in Sections 2.2, 2.3 describes the thermo- mechanical analysis of the two selected configuration to estimate the temperature distribution and the stress acting on the configurations. Finally an optimized configuration is selected for improving the FW design in section 2.4. Detailed thermal-hydraulic analyses of updated design of the TBM FW to estimate the temperature distribution, along with the validation of analytically calculated pressure drop and HTC is discussed in Section 3. The results of updated design for transient and accident conditions based on ITER operating condition [4,5] are discussed in Section 4.

* Corresponding author.
E-mail address: deepaks@ipr.res.in (D. Sharma).

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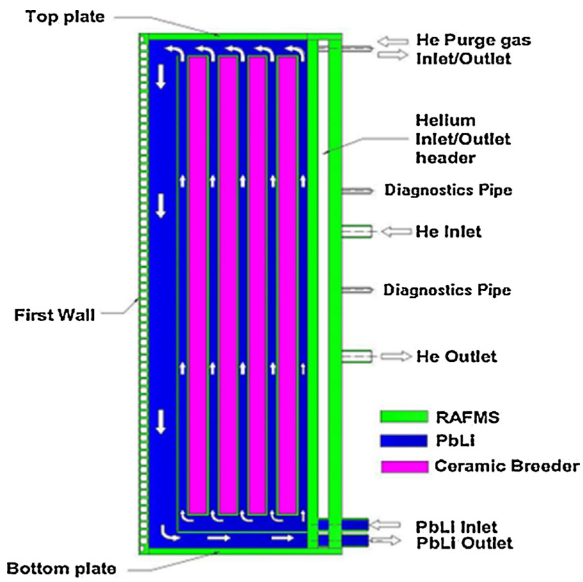

Fig. 1. 2 D view of LLCB TBM.

2. FW design

The CDR design [2] of LLCB TBM FW has a total of 65 coolant channels with 13 circuits (5 channels per circuit); each channel is 20 mm wide and 20 mm in height as shown in Fig. 2. Fig. 2(a) and (b) shows the overall dimension of the FW, and the top view of FW with manifolds, respectively. Fig. 2(c) and (d) shows the serpentine coolant flow path in one circuit, and the FW cross section, respectively. The total mass flow requirement of Helium for cooling the entire FW is 1.6 kg/s with an outlet temperature of 340 C [6].

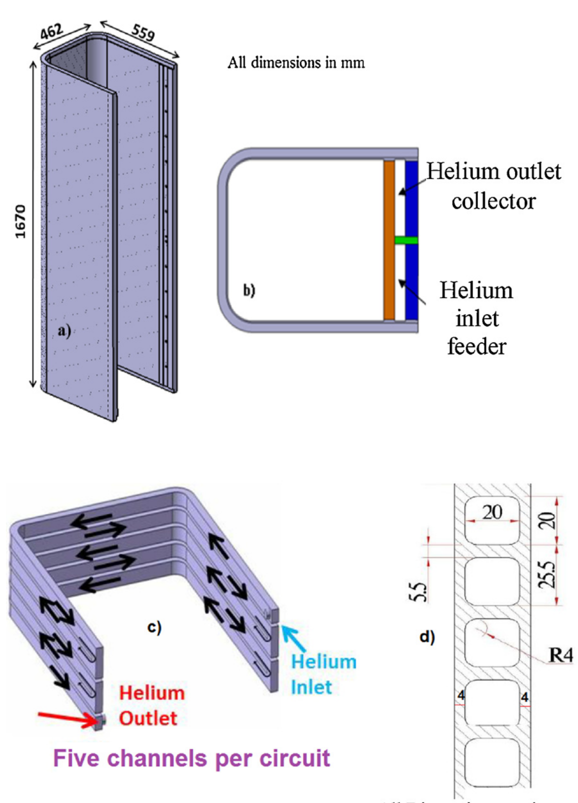

Fig. 2. FW of CDR design of LLCB TBM.

To improve the FW design, the main objective is to achieve reduction in flow rate of helium with higher outlet temperature for improving the efficiency and thereby reducing the load on helium cooling systems within the constraints like structural temperature limit and available pumping power to accommodate the pressure drop. Therefore the design has to consider the requirements that the maximum temperature of first wall remains within the material limit of 550 C [7] and the flow in the FW circuits should not exceed the pressure drop of 0.25 MPa. This limit has been set such that pressure drop in FW circuits is not more than 25% of the total pressure drop that occurs in the full helium loop which also has other components like piping, valves, heat exchangers, manifolds etc and this pressure drop is accommodated by the helium circulator. Pressure drop of 1.2 MPa occurs in the helium loop which has been calculated using RELAP code in [6] which shows suction and discharge pressure of 7.6 MPa and 8.8 MPa respectively across the helium circulator. The stresses should be also within the limits as per RCC–MR 2007 [8] design rules for P type ($P_m < S_m$, $P_m + P_b < 1.5\ S_m$) against primary loading and S type ($P_m + P_b + \Delta Q < 3S_m$) against primary + secondary loadings, where P_m is primary membrane P_b is primary bending and ΔQ is secondary membrane + bending stresses, S_m is allowable stress for the material.

The overall thickness of FW is kept 28 mm with 4 mm thickness (distance of cooling channel from plasma facing surface) in the front. The analytical study has been performed for four different configurations, viz. the 20 × 20 mm square channel configuration, 20 mm diameter circular channel, 15 × 15 mm square channel and 15 mm diameter circular channel. The inputs are mass flow rates (0.8–1.6 kg/s) and no. of circuits (16, 13, 11, 9, and 7). For a particular mass flow and no. of circuits, the thermal performance (HTC, maximum temperature) and pressure drop has been evaluated for all four channel configurations. The no. of circuits are kept same for all configurations and the total number of channels and the number of channels per circuit are varied accordingly. Based on the channel configuration, the heat transfer coefficients, outlet temperature, pressure drop are calculated.

2.1. Parameters for FW design

The various parameters required for first wall design namely HTC (Heat transfer coefficient), bulk temperatures, pressure drop and FW temperatures are calculated using the correlations and analysis defined below:

2.1.1. HTC and bulk temperature calculation

Heat transfer coefficients are calculated using Gnielinski equation [9,10] given by Eqs. (1) and (2) where Nu is Nusselt number, Re is Reynolds number, Pr is Prandtl number and ξ is friction factor.

$$Nu = \frac{\frac{1}{8}\xi(\mathrm{Re}-1000)\mathrm{Pr}}{1 + 12.7\sqrt{\frac{1}{8}\xi}(\mathrm{Pr}^{2/3} - 1)} \tag{1}$$

$$\xi = \frac{1}{(1.82\log \mathrm{Re} - 1.64)^2} \tag{2}$$

Prandtl number for the helium is ~0.66. Nusselt number is calculated from this above Eq. (1) whose range of validity is $0.5 < Pr < 1.5$, $2300 < Re < 10^6$ and heat transfer coefficients are estimated using the calculated Nusselt number. The calculated outlet temperature by energy balance is considered as bulk fluid temperature.

2.1.2. Pressure drop calculation

Pressure drop is calculated from correlations and data given in "*Handbook of hydraulic resistance*" [11] from Eqs. (3)–(6) where ρ is fluid density, *f* is friction factor, *l* is length of channel, *v* is mean fluid velocity, *D* is hydraulic diameter and *K* is concentrated loss factor.

Frictional pressure drop due to flow length of a circuit: