LOFA analysis in helium and Pb-Li circuits of LLCB TBM by FE simulation

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Abstract. One of the main ITER objectives is to demonstrate the feasibility of the breeding blanket concepts that would lead to tritium self-sufficiency and the extraction of a high-grade heat for electricity production. India has developed the LLCB TBM to be tested in ITER for the validation of design concepts for tritium breeding blankets relevant DEMO and future power reactor. LLCB concept has the unique features of combination of both solid (lithium titanate as packed pebble bed) and liquid breeders (molten lead lithium). India specific IN-RAFMS is the structural material for TBM. The First Wall is actively cooled by high-pressure helium (He) gas [1]. It is important to validate the design of TBM to withstand various loads acting on it including accident analysis like LOCA, LOFA etc. Detailed thermal-hydraulic simulation studies including LOFA in helium and Pb-Li circuits of LLCB TBM have been performed using Finite Element using ANSYS. These analyses will provide important information about the temperature distribution in different materials used in TBM during steady state and transient condition. Thermal-hydraulic safety requirement has also been envisaged for the initiation the FPPS (Fusion Power Shutdown System) during LOFA. All these analysis will be presented in detail in this paper.

1. Introduction

India is developing Lead-Lithium cooled Ceramic Breeder (LLCB) TBM for testing in one half of the ITER port no.2. It contains lithium meta-titanate (Li₂TiO₃) ceramic breeder (CB) as the tritium breeder material in the form of packed pebble beds. Molten Pb-16Li eutectic acts as tritium breeder, neutron multiplier and coolant for the CB zones. India specific Reduced Activation Ferritic Martensitic Steel (IN-RAFMS) is the structural material for TBM. The First Wall (FW) of LLCB TBM is actively cooled by high-pressure helium (He) gas. One of the functions of FW of is to remove surface heat flux and energy from plasma during normal and off-normal ITER operational conditions [1]. During the various ITER operating conditions, the LLCB TBM set will be subjected to a complex load scenario. It is necessary to perform a detailed analysis corresponding to different operating conditions by a very systematic approach based on the load specifications [2]. It is important to validate the design of TBM to withstand various loads acting on it including accident analysis like LOCA, LOFA etc. Detailed thermal-hydraulic simulation studies of loss of flow analysis (LOFA) in both helium and Pb-Li circuits of LLCB TBM have been performed using Finite Element (FE) using ANSYS. These analyses will provide important information about the temperature distribution in different materials during the accident condition. Thermal-hydraulic safety requirement has also been envisaged for the initiation the
FPPS (Fusion Power Shutdown System) during LOFA. All these analysis will be presented in detail in this paper.

2. LLCB TBM Description

LLCB TBM set consists of LLCB TBM and Shield Block (SB) as shown in figure 1 along with its dimensions. The TBM set is welded to the flange, which is bolted to the port plug frame. Figure 2-2 shows the 3D and 2D view of LLCB TBM and its internals. The LLCB TBM has both the features of solid breeder and liquid breeder blankets. It contains lithium meta-titanate (Li$_2$TiO$_3$) as ceramic breeder (CB) material in the form of packed pebble beds and Pb-Li eutectic as tritium breeder material. Pb-Li also acts as neutron multiplier and coolant. India specific Reduced Activation Ferritic Martensitic steel (IN-RAFMS) is used as the structural material for the LLCB TBM. The shield block is located behind the LLCB TBM, for shielding from high energy neutrons to magnets and other ITER components behind the TBM set and port plug. The shield block is connected to the TBM by attachments as shown in figure 2(a). The Pb–Li flows around the ceramic breeder pebble bed compartments as shown in figure 2(b) in low velocity to extract the volumetric heat in Pb-Li and also ceramic breeder zones due to fast neutrons.

![Figure 1. LLCB TBM with shield block and attachment plates](image)

During plasma operation LLCB TBM is cooled by two process fluid: (i) 8 MPa helium is used to cool the FW structures and (ii) 1.2 MPa Pb-Li cools all CB zones and also the heat generated in Pb-Li. Apart from the two coolant circuits, low pressure helium purge gas at 0.12 MPa absolute pressure is flown through the ceramic breeder box to extract tritium generated within the ceramic breeder canister box. Tritium generated in Pb–Li circuit is extracted separately by low-pressure purge helium gas mixed with hydrogen and external detritiation system.
2.1. First Wall of LLCB TBM

The First wall (FW) assembly of LLCB TBM is designed to withstand the heat flux from the plasma and neutronics heat generation on the FW structure to maintain its temperature below the allowable limits. The typical dimension of the FW is 1670 mm (poloidal) × 462 mm (toroidal) × 559 mm (radial) which is connected helium inlet and outlet manifolds as shown in figure 3(a). FW of LLCB TBM is made of 28 mm thick U-shaped structure made of low-activation IN-RAFMS, having 65 square cooling channels. The 65 coolant channels are divided into 13 circuits. Each circuit is having 5 channels of 20 mm × 20 mm cross section as shown in figure 4. The flow direction in five channels is also shown in this figure. Velocity of helium in each channel of ~ 50 m/s corresponds to a mass flow rate of 0.125 kg/s which gives rise to a temperature difference of ~ 40 °C between inlet and outlet for the incident heat flux of 0.3 MW/m². The inlets and outlets of each channel are connected to the respective headers formed by two back plates at the backside of the TBM as shown in figure 3(b). For all 13 circuits, helium enters from the inlet header side and after passing through the five passes it is collected in the outlet header.

Figure 2. (a) 3D view of LLCB TBM along with the support structure and process pipes, (b) Pb-Li flow path in 2D view.

Figure 3. (a) FW of LLCB TBM and (b) inlet and outlet manifolds of helium (remove box).
2.2. Internal components in LLCB TBM

The internals of LLCB TBM consisting of four ceramic breeders (CB) zones, Pb-Li flow paths and the Pb-Li separator plate as shown in the top view of LLCB TBM in figure 5. It shows the nomenclature of different ceramic breeder (CB) canisters and lead-lithium (LL) channels. All CB canisters are cooled by Pb-Li and its flow arrangement is shown in figure 2(b). Pb-Li enters at 300 °C and the flow is forced upwards through a set of five parallel channels. Pb-Li removes the heat generated in CB zones and also within it and finally reaches the top header. The accumulated Pb-Li flow through first Pb-Li channel (LL1) and exits the TBM. All CB canisters have the same thickness of 50 mm. All Pb-Li parallel flow paths have the same widths of 23 mm.

3. Steady state analyses

Steady state thermal analysis has been carried out using ANSYS Finite element (FE) code to estimate the temperature of different components of LLCB TBM. Thermal loads and boundary conditions (BCs) are applied on the FE model include the surface heat flux 0.3 MW/m², neutron heat generations (volumetric heating) in different components of LLCB TBM based on the ITER neutron wall loads of 0.78 MW/m². Convective BCs (heat transfer coefficient (HTC) and bulk temperature of the fluid) have been applied on the coolant channel surfaces [3]. Optimized value of HTC of helium has been used to keep RAFMS material within its allowable temperature window. Figure 6 shows the temperature profile of LLCB TBM for ITER normal operation. The maximum temperature of 920.25 °C occurs in first CB zone (CB1). FW structure temperature ranges from 302 to 474 °C which is below the maximum allowable limit of 550 °C as shown in figure 6.
4. Transient analyses

Transient thermal analyses were performed, in 2D model for different ITER heat load conditions i.e.,
cyclic loads defined as inductive and non-inductive operations by the typical ITER pulses. Both these
operations have two scenarios of normal and fusion power excursions. Figure 7 shows the
Temperature-Time histories in different components in LLCB TBM during inductive normal
operation. It has been observed that after each pulse cycle, the temperature inside CB bed appreciably
increases. FW temperature doesn’t rise with each pulse unlike ceramic breeder temperature. During
power excursion the FW temperature reaches to 499 °C which also below its limiting value. The
details of the transient analyses for inductive and non-inductive operation can be found in ref. 3.

5. Loss of Flow Accident (LOFA)

5.1 LOFA in First Wall cooling circuit

LOFA in FW Helium Cooling System (FWHCS) occurs due to helium circulator trip causing loss of
flow of helium. During this event, it is assumed that the Pb-Li flow in LLCS loop is maintained at its
nominal operating parameters. In the safety design of LLCB TBS, it is assumed that on the low flow
signal from FWHCS, Fusion Plasma Shutdown System (FPSS) is triggered [4]. Failure of FPSS will lead to failure of TBM FW and subsequent in-vessel helium coolant leak. The temperature evolution TBM FW during LOFA is shown in figure 8. LOFA in He circuit initiated after 60 s full power flat top and the FW reaches 550 °C in 17 s. Since the time required to initiate FPPS is 3-4 s, therefore, sufficient margin for fast plasma shutdown. The same has been analyzed using RELAP/MOD4.0 and found to be in very good agreement [5].

Figure 8. Temperature-Time history in FW during FWHCS LOFA.

5.2. LOFA in Pb-Li cooling circuit
LOFA in Lead Lithium Cooling System (LLCS) occurs due to pump trip and will lead to stagnant Pb-Li in TBM. This case is studied with helium flow in FWHCS maintained at its nominal operating parameters. The increase in Pb-Li temperature will cause the temperature of CB canister to rise because of no heat transfer from Pb-Li to them. Temperature evolution of internal components of LLCB TBM during LLCS LOFA is shown in figure 9. The time duration is long enough to go for slow plasma shut down (instead of FPSS) in order to bring down the Pb-Li and CN canister structure zone temperatures within the allowable limits i.e. 480 °C (above which the corrosion in structural material increases rapidly). There is no significant temperature variation in TBM FW during LOFA in LLCS.

Figure 9. Temperature-Time history in FW during LLCS LOFA
6. Summary
Temperatures in LLCB TBM are well within the allowable limits in ITER inductive and non-inductive (normal and power excursion) operations. During LOFA in FW cooling circuit, the FW reaches its limiting temperature of 550 °C in 17 s. Actuation of FPSS is recommended to keep the TBM FW temperature below design limit during LOFA in FWHCS. Slow plasma shutdown following the pump trip (LOFA) in LLCS will be enough for the temperatures to remain under design limit. Time duration long enough to go for slow plasma shut down (instead of FPSS) in order to keep the TBM temperatures within the allowable limits (< 480 °C for LLCS operation) The results obtained from FE analyses are compared with accident analysis using RELAP/MOD4.0 and found to be in good agreement. LOFA and LOHS (Loss of Heat Sink) in FWHCS and LLCS are analyzed, the objective of these analyses is to provide the safety design inputs for I&C safety functions.

References
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