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Safety Analysis on the Korean He-Cooled Molten Lithium Test Blanket Module for the ITER

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ABSTRACT

Through a consideration of the requirements for a DEMO-relevant blanket concept, a He Cooled Molten Lithium (HCML) blanket with Ferritic Steel (FS) as a structural material is proposed to be tested in the International Thermonuclear Experimental Reactor (ITER). The HCML Test Blanket Module (TBM) uses He as a coolant at an inlet temperature of 300°C and an outlet temperature up to 376°C and Li is used as a tritium breeder by considering its potential advantages. Two layers of a graphite reflector are inserted as a reflector in the breeder zone to increase the Tritium Breeding Ratio (TBR) and the shielding performances. A 3-D Monte Carlo analysis is performed with the MCCARD code for the neutronics and the total TBM power is designed to be 0.739 MW at a normal heat flux from the plasma side. From the analysis results with CFX-10 for the thermal-hydraulics, the He cooling path is optimized and it shows that the maximum temperature of the first wall does not exceed 550 °C at the structural materials and the coolant velocities are 45 m/sec and 8.2 m/sec in the first wall and breeding zone, respectively. The obtained temperature data is used in the thermal-mechanical analysis with ANSYS-10. The maximum von Mises equivalent stress of the first wall is 123 MPa and the maximum deformation of it is 3.73 mm, which is lower than the maximum allowable stress. The KO HCML is being designed and optimized from the current design.

Since the safety analysis related to the postulated accident is essential for both licensing and acceptance for installation in ITER, the relatively severe cases were assumed for the safety assessment; (1) active plasma shut-down after delayed accident detection with disruption and (2) no active plasma shut-down. The safety analysis performed for both cases show the capability of decay heat removal in both cases.

1. INTRODUCTION

One of the main engineering performance goals of ITER is to test and validate the design concepts of the
tritium breeding blankets relevant to a power producing reactor. The tests will focus on modules including a demonstration of the breeding capability that will lead to a tritium self heat suitable for an electricity generation. In Korea, TBMs such as a Helium Cooled Solid Breeder (HCSB) and the HCML are being designed according to the concept of the KO DEMO. Since the safety analysis such as operational release, waste, accident analysis, FMEA, etc. are essential in order to install the KO HCML TBM into ITER machine, the preliminary safety analysis is performed with the postulated accident scenario. In this paper, the proposed HCML TBM designs, its performance analysis, and preliminary safety analysis results are introduced.

2. DESIGN AND PERFORMANCE ANALYSIS

The HCML TBM uses He as a coolant at an inlet temperature of 300 °C and an outlet temperature up to 400 °C and Li is used as a tritium breeder. Its potential advantages are as follows: virtually no concern for a T permeation into the coolant system; simplified high-performance system with a He-direct cycle; alleviated material problems due to a very slow Li flow speed; no concern for a Li fire in an inert gas environment; marginal MHD (Magneto-Hydro-Dynamics) effects due to a very slow Li flow; no Po-210 & Hg-204 generation; Li loop as a redundant cooling circuit in the case of a He loss accident. With one- or two layer(s) of a graphite reflector inserted in the breeder zone, the TBR and the shielding performances can be increased. A sensitivity study has been carried out to optimize the graphite reflector thickness and $^6$Li enrichment (optimum is found for a natural enrichment). In a graphite-reflected HCML blanket, a self-sufficient TBR can be achieved without any special neutron multiplier.

Figures 1 and 2 depict the schematic and breeding zone of the KO HCML TBM concept. The whole TBM is cooled by the He coolant alone and the molten Li is only used as the tritium breeder. It is well known that liquid Li is compatible with steel up to 550 °C. Due to the low speed of the molten Li, there are no serious MHD and material corrosion issues. With the HCML TBM concept, the heat exchanger design is relatively simple since the liquid Li is not involved in the heat removal. A graphite reflector is used in this TBM concept in order to minimize the neutron leakage from the TBM. Based on the neutronic analysis, the graphite reflector is placed such that the TBR is maximized: a thick front region and a thin back breeder. In the ITER machine, the Li inventory is limited due to the safety reason, the amount of Li in the HCML TBM is about 28 liters, which satisfies the Li limit. The Li-6 enrichment in the current design is 12 wt%, corresponding to an optimal value in terms of the TBR. It is expected that the Li speed will be very slow, less than a few mm/sec for the design.

For the model in figure 2, a 3-D Monte Carlo analysis is implemented with the MCCARD code. The design data and nuclear performance of HCML are given in Table 1. The total heat deposition is substantially lower than in the HCSB case since the HCML TBM does not contain any neutron multiplier, i.e. Be. Also, the TBR of the TBM is less than unity. This is mainly because the Li inventory is limited in the ITER design. In the actual DEMO-like design, the front Li breeder region could be significantly expanded for a higher value of the TBR. However, a low TBR does not matter in the TBM because the main purpose of the TBM is to confirm the first principle of the proposed TBM. As a result, the tritium production rate is relatively small, too.

Thermal-hydraulic analysis is also performed in order to calculate the temperature distribution of the first
wall and the breeding zone by using the CFD code, CFX-10. Figure 3 shows the He flow paths for the entire HCML and first wall. The helium coolant flows through the first wall and then half of the inlet He flows into the breeding zone in a poloidal direction at a static pressure of 8 MPa. When the inlet temperature is assumed to be 300 °C, the He temperature is 334 °C at the first wall exit. The coolant flow rate for the HCML with a thermal power of 0.739 MW and a coolant velocity of 45 m/sec is 2.2 kg/s. The thermal-hydraulic design parameters of the KO HCML are summarized in Table 1. The temperature distributions of the HCML are calculated by using a 3D model of the first wall and the breeding zone, separately. The average surface heat fluxes of 0.3 and 0.5 MW/m² from a plasma are applied to the surface of the Be armor. The helium coolant temperatures used in this analysis are 320 °C and 330 °C in the first wall channel inlet for each surface’s heat fluxes. Figures 4 and 5 show the predicted temperature distributions at each region. The peak temperatures are predicted to be 466.2 and 486.7 °C at the first wall channel and the Be armor, respectively at a normal heat flux. Similarly, The maximum temperatures are predicted to be 559.3 and 592.7 °C at the first wall channel and Be armour, respectively at a peak heat flux. In the breeding zone, maximum temperature is obtained with 625 °C in the front graphite reflector and more a detailed distribution of temperature is shown in figure 6. The pressure drops of the coolant in the HCML are 6788 and 263 Pa for each single channel of the first wall and the breeding zone, respectively.

Using the CFD model of the first wall for the HCML, a finite element model for the thermal analysis is created by ANSYS Version 10.0. The boundary conditions are determined from the results of the CFX-10 analysis. The maximum von Mises equivalent stress of the first wall is 123 MPa and the maximum deformation of it is 3.73 mm, which is lower than the maximum allowable stress as shown in figure 6. [2].

From the thermal-hydraulic analysis, the flow distribution is assumed to be a uniform velocity at every channel. However, the actual flow should be investigated through an analysis and the CFX-10 code is used in this study. Figure 7 shows a flow distribution from the back wall manifold to first wall channels and the mass flow fractions for each channel are 9.6 % to 11.0 %. And also, the flow distribution from the top-cover to the breeding zone and from the back wall manifold to the top-cover are currently being investigated.

3. PRELIMINARY SAFETY ANALYSIS

The safety analysis related to the postulated accident is essential for both licensing and acceptance for installation in ITER. For the safety assessment, three groups of accidents such as (1) in-vessel TBM Loss-of-coolant-accident (LOCA), (2) in-TBM breeder box LOCA, and (3) ex-vessel TBM LOCA should be judged to cover all accident scenarios address behavior of the TBM under hypothetical accident scenarios and to assess the ultimate safety margins of the TBM. In the present paper, two cases of ex-vessel LOCA have been studied:

(1) active plasma shut-down after delayed accident detection with disruption and
(2) no active plasma shut-down.

To simulate the cases, 3D model for first wall and 2D model for entire first wall and breeding zone are prepared as shown in figure 8 and the simulations are performed with CFX-10. For the case (1), the HCML TBM behavior has been assessed assuming that the accident can be detected only after 10 seconds due to the failure of detection. Then, the plasma disrupts and the surface heat flux reaches 5.5 MW/m² during 100 ms. During the
transient, 13.1 seconds, the nuclear heating remains at nominal values and decay heat is not taken into account after this time. Figure 9 shows the temperature evolutions for first wall and breeding zone, respectively. Be armor and first wall temperatures reach up to 900 °C and 800 °C. And their temperature is recovered after 1000 sec. Case (2) assumes that the accident remains undetected and the plasma continues to burn with the peak surface heat of 0.5 MW/m² until the first wall reaches a temperature of 1100 °C. At this temperature, the beryllium layer starts to sublimate into the plasma and stops it so that the surface heat flux drops to zero. The calculations performed indicate that the first wall temperature reaches this temperature about 34 sec after the beginning of the accident. Figure 10 shows the temperature evolutions for first wall and breeding zone, respectively. Be armor and first wall temperature reach up to 1350 °C and 1250 °C. And their temperature reaches 580 °C after 10000 sec.

In the present preliminary safety analysis, the only temperature evolution at each region is being investigated but stress intensity should compare with the allowable criteria. The other accident scenarios and stress analysis is being investigated and will be completed in the near future.

4. CONCLUSIONS

In order to participate in the test program of the tritium breeding blanket in the ITER, we have been designing our own HCML TBM with regards to the Be amount and a Graphite application, and these concepts have been investigated in terms of their neutronics, thermal-hydraulics, and thermo-mechanics. The final design of HCML TBM will be completed through the above procedure considering the safety and cooling efficiency. Two cases of ex-vessel LOCA have been studied and they show the capability of natural cooling when accident occurs. More accident analysis including other safety related investigations will be performed in the near future.

REFERENCES

7. Personal Communication at 2nd Japan-Korea workshop on ITER blanket, March 31-April 1, 2005.
Figure 1 The 3D CATIA model of the KO HCML TBM

Figure 2 The cross-section view of the KO HCML TBM
Table 1 Design data and nuclear performance of the KO HCML

<table>
<thead>
<tr>
<th>Structural material</th>
<th>Eurofer</th>
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<tr>
<td>Coolant</td>
<td>He gas</td>
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<tr>
<td>Reflector</td>
<td>Graphite</td>
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<tr>
<td>SHF (avg. &amp; peak), MW/m²</td>
<td>0.3, 0.5</td>
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<tr>
<td>NWL, MW/m²</td>
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<tr>
<td>FIRST WALL are, m²</td>
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<tr>
<td>Heat deposition, MW (at avg. SHF)</td>
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<td>T production rate, g/FPD</td>
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<td>Local TBR</td>
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<tr>
<td>Coolant temperature [°C] (inlet/FIRST WALL outlet/outlet)</td>
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<tr>
<td>Cooling system pressure [MPa]</td>
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<td>Coolant mass flow rate [kg/s]</td>
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</table>
Figure 3 He flow scheme and its temperature at first wall channels

Figure 4 Computational model and temperature distribution for the first wall of the KO HCML
Figure 5 Calculated temperature distribution for the KO HCML.
Figure 6 Thermal deformation and stress distributions for the first wall of the KO HCML
Figure 7 Flow distribution at the back wall of the KO HCML

Figure 8 3D (a) and 2D (b) model for safety analysis
Figure 9 first wall and breeding zone temperature evolutions at case (1)
Figure 10 first wall and breeding zone temperature evolutions at case (2)