Progress in the Design of a Tritium Breeding Blankets for Testing in ITER

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Abstract. Korea has developed two DEMO relevant blanket concepts for testing in the ITER; one is the He Cooled Solid Breeder (HCSB) blanket and the other is the He Cooled Molten Lithium (HCML) blanket. HCSB blanket uses a Li-based compound, Li_2SiO_4, as a breeder, Be as a neutron multiplier and high pressure (8 MPa) He as a coolant. The HCML blanket uses Li as a breeder and high pressure (8 MPa) He as a coolant. Both TBMs use Ferritic/Martensitic Steel (FMS) as a structural material and graphite as a reflector to minimize the neutron leakage. Design of TBMs have been optimized through neutronic, thermal-hydraulic and thermo-mechanical performance analyses.

1. Introduction

The fusion energy development strategy in the Korea National Basic Plan consists of several major programs: (1) KSTAR for the study of a long-pulse, advanced tokamak operation, (2) ITER for the burning plasma experiment, (3) DEMO for the demonstration of producing a net electricity, and (4) a commercial fusion reactor. DEMO is regarded as the last step before the development of a commercial fusion reactor. The widely accepted common requirements of DEMO are as follows. First, it should demonstrate a net electric power generation. Second, it should demonstrate a tritium self sufficiency. And last, it should demonstrate the safety aspect of a power plant and it should be licensable as a power plant.

One of the main engineering goals of ITER is to test and validate the design concepts of the tritium breeding blankets relevant to a DEMO reactor. Korea proposed two DEMO relevant blanket concepts for testing in the ITER [1]; one is the Helium Cooled Solid Breeder (HCSB) blanket and the other is the He Cooled Molten Lithium (HCML) blanket.

In the HCSB TBM design, the amount of Be is reduced by replacing some of it with graphite for a neutron reflector, while tritium breeding ratio (TBR) remains almost unchanged with relatively low ^{6}Li enrichment ~ 40 %. For the ceramic breeder, Li_4SiO_4 with a 97 % TD and 62 % packing fraction is used and for the Be multiplier, a 95 % TD and 80 % packing fraction is used. The graphite is also used in a pebble-bed form in order to accommodate any possible geometrical changes during a neutron irradiation. The packing fraction of the graphite is assumed to be 85% in this design. Using the thick graphite reflector provides an advantage that it can play a role of a heat sink in the case of a loss of coolant accident.

Potential advantages of HCML concept 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. In a graphitereflected HCML blanket, a self-sufficient TBR can be achieved without any neutron multiplier. The thickness of graphite reflector and ^{6}Li enrichment can be optimized through a sensitivity study (optimum was found for a natural enrichment, [2]). But for testing in ITER, enrichment of ^{6}Li is 90 wt% since the amount of Li is limited due to safety reasons. [3]

2. Design and performance analysis of KO HCSB

The HCSB TBM consists of the following main components, First Wall (FW), Side Wall (SW), Breeding Zone (BZ), and back manifold. The FW is the plasma facing components to withstand neutron and heat flux from the plasma. The SW is used for enclosing the HCSB TBM, which gives rigidity to the structure. Figure 1 shows the overall view of the HCSB TBM. The dimension was updated since the size of the ITER common frame to accommodate TBMs had been reduced. All the ceramic breeders are used with ^{6}Li enrichment of 40 % except that the first layer is used with natural Li to relieve heat flux to the first wall.

Power deposition by the neutron wall loading and surface heat flux from the plasma is extracted by the helium coolant. The coolant path is depicted in Figure 2 by eight steps. The helium enters from the outer He pipe (1) and is distributed to the FW channels in Manifold 1 (2). Although the helium goes upward in Figure 2, it flows in a counter direction between adjacent channels in order to minimize temperature differences. After having cooled the FW (3), the helium comes to Manifold 2 (4) and distributed to the SW pipes. Again the counter cooling scheme is adopted in the SW cooling. Figure 2 shows right going helium flow in Manifold 2 (4-5). The helium coming back from the SW and BZ (6) is collected in Manifold 3 (7) and leaves through the inner He pipe (8). Tritium produced from the BZ is extracted by the purge gas. The purge gas path and design of its manifold system is now in progress.

For the HCSB design and analysis, neutronics analysis including burn-up (transmutation) computation is required to calculate more accurate neutron flux and tritium production rate. The MONTEBURNS code [4] the which is widely used for burn-up calculations in the fission reactor design is modified to solve the fusion blanket problem including Be^{9}(n,t)Li^{7} and Li^{7}(n,n't)α reactions. The previous HCSB TBM configuration was considerably changed in order to increase efficiency of the breeder regions. A latest radial configuration of the HCSB

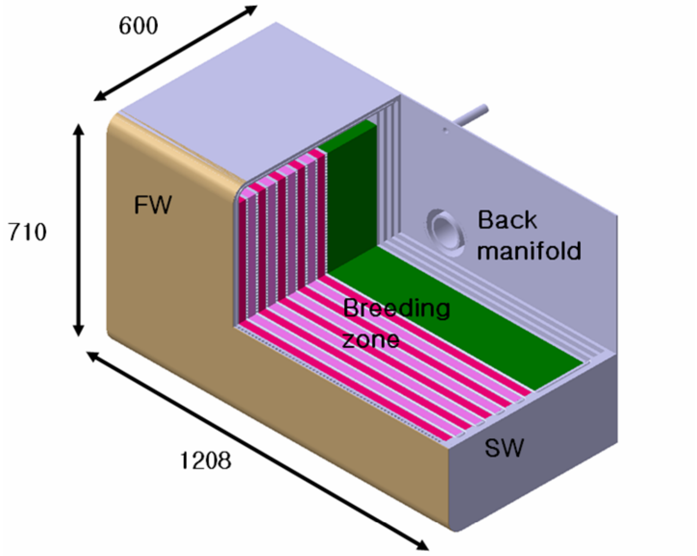
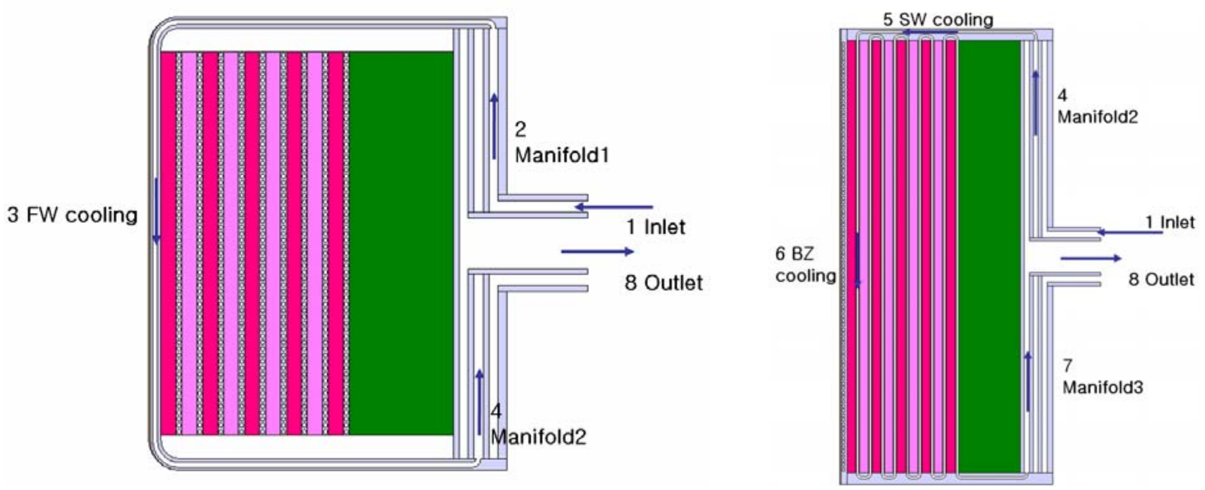


FIG. 1. HCSB TBM design



(a) Side section view *(b) Top section view*

FIG. 2. Helium coolant path

TBM is summarized in Table 1. Local TBR and global TBR are calculated to be 1.10 and 1.07, respectively for 0.78 MW/m^2 of a neutron wall loading. Calculations based on refined models are being carried out And further optimization is also anticipated.

TABLE 1*:* RADIAL DIRECTIONAL CONFIGURATIONS OF THE HCSB TBM

Material	Radial Thickness (mm)
Be coating	3
First Wall (Eurofer)	18
Li4SiO4 (Natural Li)	20
Beryllium	40
Li4SiO4 (40% enriched Li)	20
Beryllium	40
Li4SiO4 (40% enriched Li)	20
Beryllium	40
Li4SiO4 (40% enriched Li)	20
Beryllium	30
Li4SiO4 (40% enriched Li)	30
Graphite	202
Back manifold	90

All components in the HCSB TBM are actively cooled by the helium coolant in radial, poloidal and toroidal direction at 8 Mpa of a pressure. The inlet and outlet temperatures of the coolant are 300 °C and 500 °C, respectively. Mass flow rate of the coolant is 1.12 kg/s for the total thermal power 1.16 MW. Due to the overall dimension changes of the HCSB TBM and layer composition changes in the BZ, the thermo-hydraulic design parameters of the HCSB TBM was updated and are summarized in Table 2. The temperature distribution of the HCSB TBM were calculated using a computational fluid code, CFX-5, for a three dimensional model. 0.3 MW/m^2 of heat flux is applied to the plasma facing surface. The heat flux from the

BZ is assumed to be 0.03 MW/m^2. Figure 4 shows the numerical result. The peak temperature in the FW is about 526 °C. The helium temperature at the outlet of the FW is calculated to be 372 °C and the pressure drop along the channel is computed as 12.1 kPa. Thermo-hydraulic analyses for the SW and BZ are now being performed along with neutronics calculations for further optimization.

TABLE 2: THERMO-HYDRAULIC DESIGN PARAMETERS

Parameter	Value
Surface heat flux from the plasma (MW/m^2)	0.3
Total thermal power Surface heat load (MW) Volumetric heat load (MW)	1.16 0.26 0.90
Coolant mass flow rate (kg/s)	1.12
Coolant pressure (MPa)	8.0
Coolant inlet/outlet temperature (°C) First wall Side wall & breeding zone	 300/370 370/500

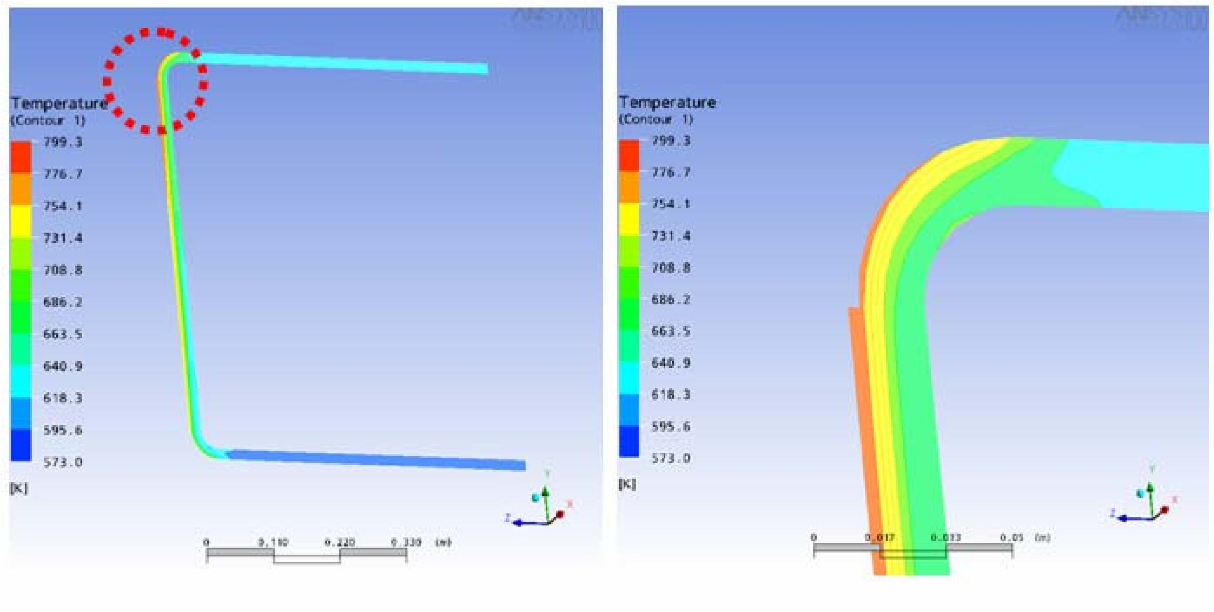


FIG. 3. Temperature distribution for the FW of the HCSB TBM

3. Design and performance analysis of KO HCML

Figure 4 depicts 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 reasons, 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.

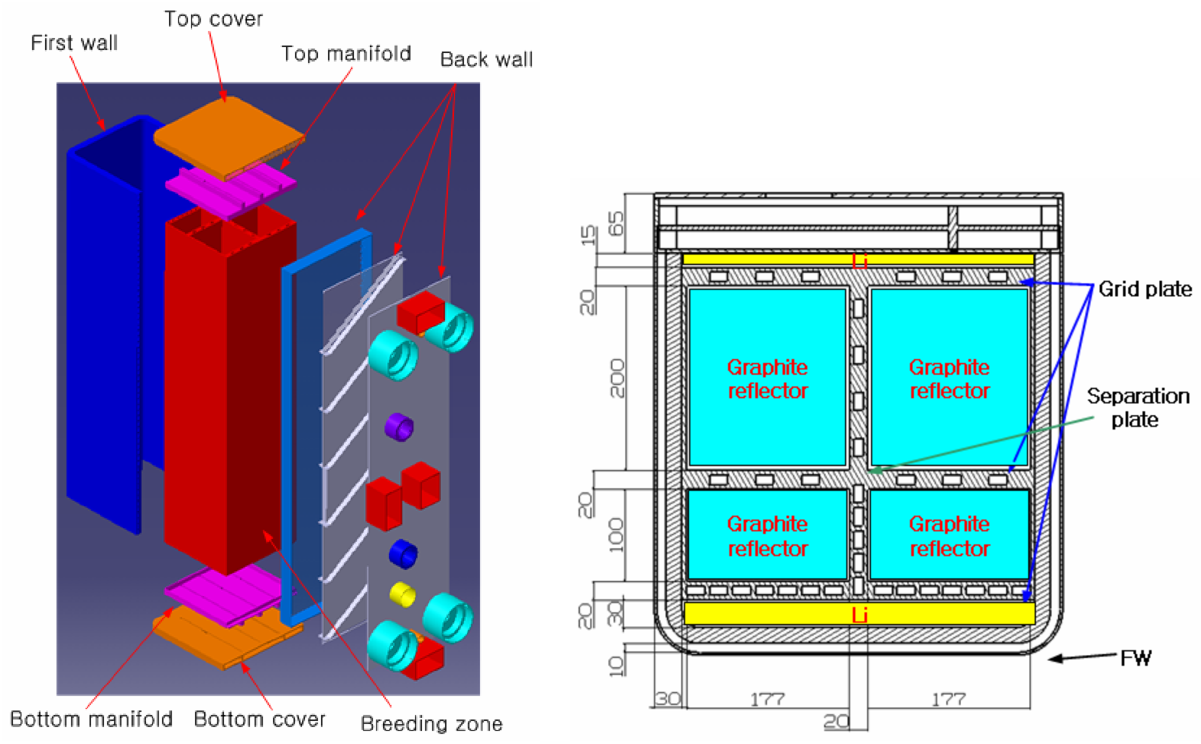


FIG. 4. Schematic of the KO HCML TBM

For the model in figure 4, a 3-D Monte Carlo analysis is implemented with the MCCARD code [5]. The design data and nuclear performance of HCML are given in Table 3. 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 5 shows the He flow paths for the entire HCML and first wall. The helium coolant flows through the first wall and then a half of it into the front and rear breeding zone in a poloidal direction at a static pressure of 8 MPa, respectively. When the inlet temperature is assumed to be 300 ^{o}C, the He temperature is 361 ^{o}C at the first wall exit. The coolant flow rate for the HCML with a thermal power of 0.675 MW and a coolant velocity of 50 m/sec is 1.22 kg/s. The thermal-hydraulic design parameters of the KO HCML are summarized and added in Table 3.

TABLE 3: DESIGN DATA AND NUCLEAR PERFORMANCE OF THE KO HCML

Structural material	Eurofer
Coolant	He gas
Reflector	Graphite
SHF (avg. & peak), MW/m^2	0.3 & 0.5
NWL, MW/m^2	0.78
FIRST WALL are, m^2	0.444 x 1.62
Heat deposition, MW (at avg. SHF)	0.675
T production rate, g/FPD	0.029
Local TBR	0.36
Coolant temperature [^{O}C] (inlet/FIRST WALL outlet/outlet)	300/361/406
Cooling system pressure [MPa]	8.0
Coolant mass flow rate [kg/s]	1.22

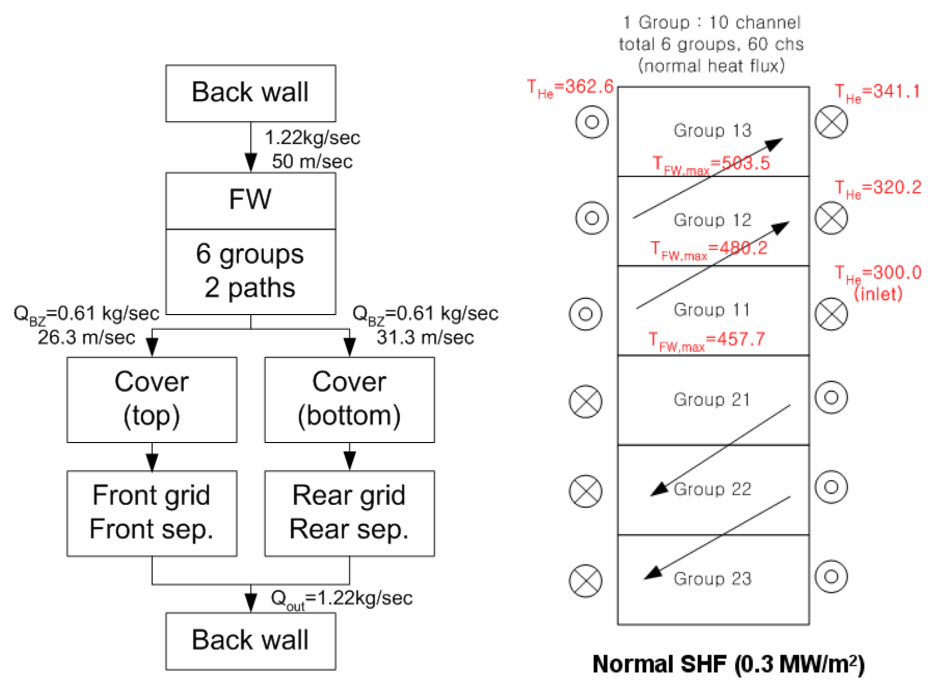


FIG. 5. He flow scheme and its temperature at first wall channels

The temperature distributions of the HCML are calculated by using a 3D model of the single first wall and the entire model with breeding zone and 60 first wall channels, separately. The average surface heat fluxes of 0.3 and 0.5 MW/m^2 from a plasma are applied to the surface of the Be armor. The helium coolant temperature used in this analysis is 300 ^{o}C in the first wall channel inlet for each surface's heat fluxes. And the heat by neutron wall loading is considered according to the distance from plasma side since the power density of each structure decreases rapidly by the distance. Figure 6 shows the predicted temperature distributions at each region in the case of 3rd path group (group 13 case in figure 5). The peak temperatures are predicted to be 503.5 and 517.9 ^{o}C at the first wall channel and the Be armor, respectively at a normal heat flux. In the breeding zone, maximum temperature is obtained with 535 °C in the front graphite reflector and more a detailed distribution of temperature is shown in figure 7. The pressure drops of the coolant in the HCML are 11.3 and 5.57 kPa for each single channel of the first wall and the breeding zone, respectively.

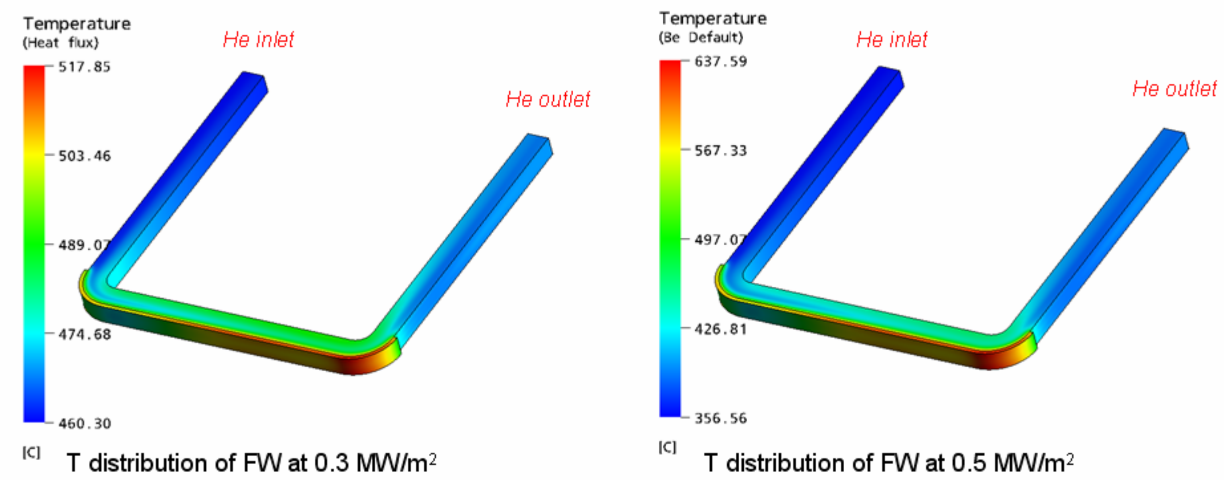


FIG. 6. Temperature distributions for the first wall of the KO HCML

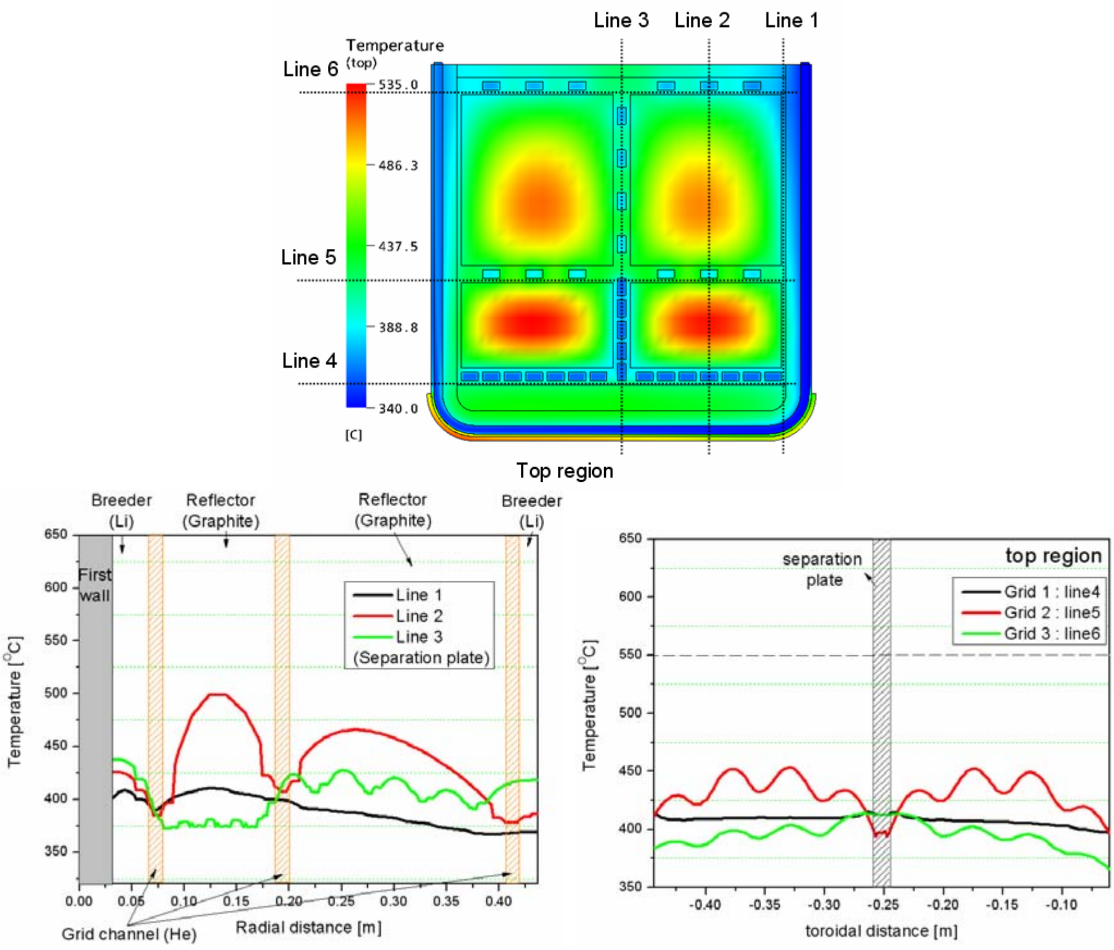


FIG. 7. Calculated temperature distribution for the KO HCML

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 the maximum deformation of the first wall is 1.3 mm and maximum von Mises equivalent stress of it is 2540 MPa as shown in figure 8. The stress value is allowable but it can cause the problem in manufacturing and it will be investigated in the future.

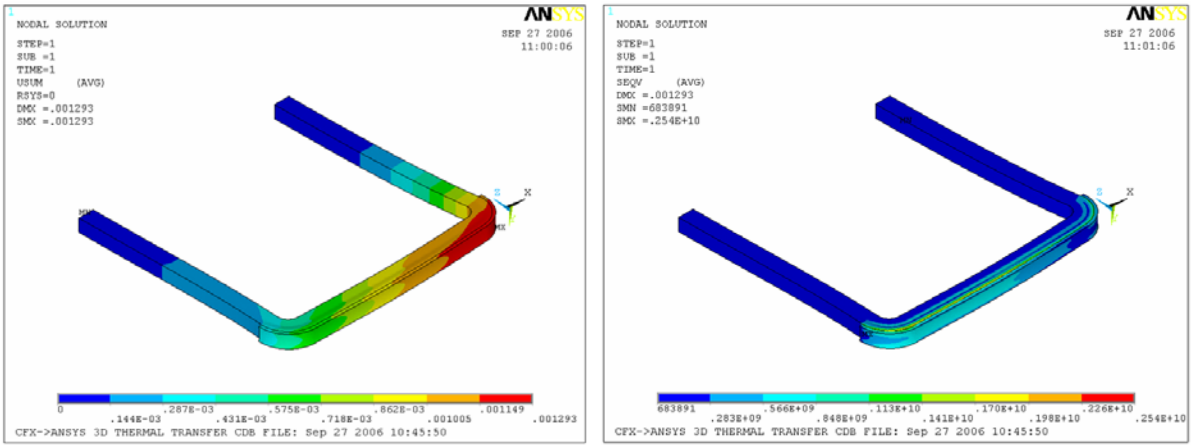


FIG. 8. Thermal deformation and stress distributions for the first wall of the KO HCML

4. Conclusions

Korea have been developing two DEMO relevant TBM concepts to participate in the test program of the tritium breeding blanket in the ITER. These concepts have been optimized through neutronic, thermal-hydraulic, and thermo-mechanical analyses. They will be tested in ITER if their acceptability for an installation is proved by suppoting R&D on key issues and safety validation.

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