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Multiple Module Simulation of Water Cooled Breeding Blankets in K-DEMO Using Thermal-Hydraulic Analysis Code MARS-KS

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1. Introduction

A preliminary concept for the Korean fusion demonstration reactor (K-DEMO) has been studied by the National Fusion Research Institute (NFRI) [1] based on the National Fusion Roadmap of Korea [2]. The feasibility studies have been performed in order to establish the conceptual design guidelines of the breeding blanket. As a part of the NFRI research, Seoul National University (SNU) is conducting thermal design, evaluation and validation of the water-cooled breeding blanket for the K-DEMO reactor.

The purpose of this study is to extend the capability of MARS-KS to the overall blanket system analysis which includes 736 blanket modules in total. The strategy for the multi-module blanket system analysis using MARS-KS is introduced and the analysis result of the 46 blanket modules of single sector was summarized.

2. Water cooled blanket concept for K-DEMO

In the proposed breeder blanket concept for K-DEMO, water-cooled multiple-layer-breeding blanket incorporates multiple layers of breeder and multiplier mixtures, cooling channels, and structural materials parallel to the first wall as illustrated in Figs. 1 and 3 [3]. Figure 1 depicts the in-vessel component segmentation (22.5°), and Fig. 3 depicts the configuration of a single blanket module that is located at the center of the outboard sector. As shown in Fig. 1, the blanket modules are segmented into 16 sectors along the toroidal direction, and each sector has 16 blanket modules in the inboard sector, 10 modules in the outboard toroidal field (TF) sector, and 20 modules in the outboard port sector. The single sector is symmetric with respect to the horizontal axis, and the blanket modules are inclined following the curvature of the vacuum vessel, as shown in Fig. 2.

Figure 4 shows a simplified concept of the blanket cooling system. The main coolant pipe is split into a manifold through the common headers for the sector inlet, and each manifold branch is connected to a blanket module. The coolant cools down and exits the blanket modules, and is collected in the common header for the sector outlet, which is connected to the main coolant pipe line. Depending on the location of each blanket module, the heat load at first wall, and the heat generation rates in the breeder, multiplier, and RAFM vary significantly; they were estimated from a preliminary neutronic analysis of each blanket module [6]. The flow rate for each module needs to be optimized in order to achieve the target temperature of 325 –330 °C at the exit of the sector outlet header. From the balance between the heat loads on each module and the fluid temperature rise, the optimum flow rates were determined, and an orifice plate was installed in each manifold branch to ensure optimum flow distribution.

A single blanket module can be described as an assembly of 106 slices in the toroidal direction, as shown in the cross-sectional top view of Fig. 3(b). A slice consists of the first wall made of 5 mm thick Tungsten, 1 mm thick vanadium, 10 layers of breeding zones filled with the mixture of Li_4SiO_4 and $Be_{12}Ti$ pebbles, and 12 cooling channels confined by the RAFM structural material. The 12 parallel flow channels in a slice are connected to the module common headers for the upper and lower part of the single module, as shown in Fig. 3(c). Pressurized water (15 MPa) enters the lower module header and flows upward along the 11 coolant channels, except along the first wall cooling channel. The water is collected in the upper module header and flows out of it towards the first wall cooling channel. Then, the water cools the first wall while flowing downward, and finally exits the blanket module through the outlet pipe.

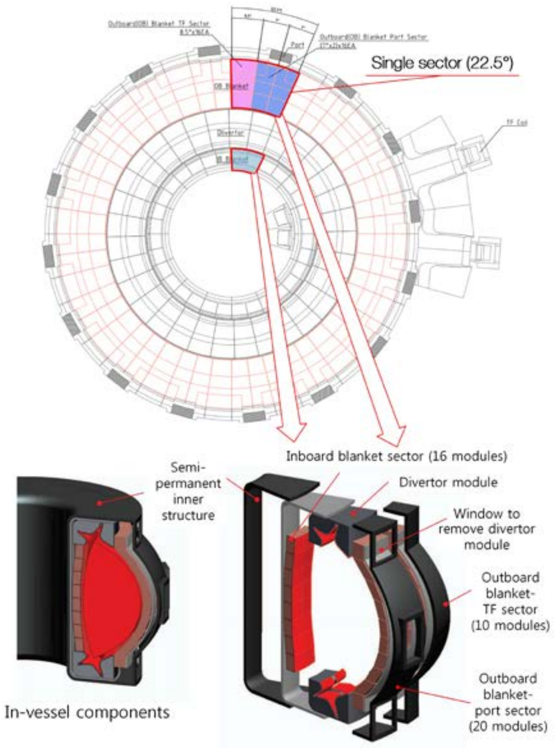


Fig. 1. In-vessel component of K-DEMO conceptual design.

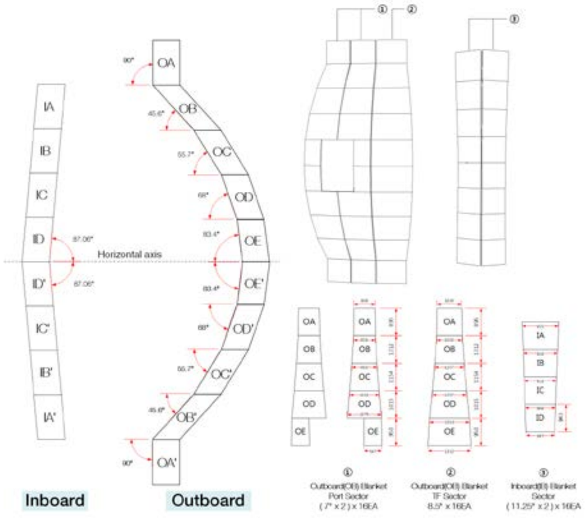
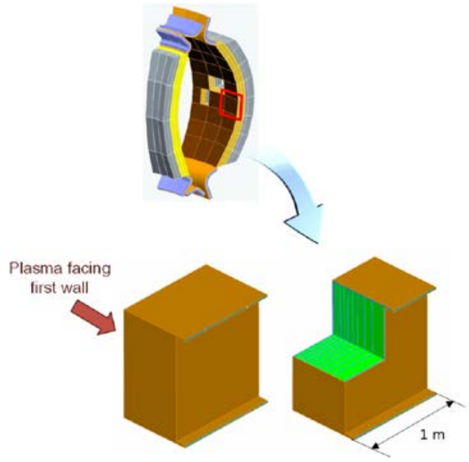
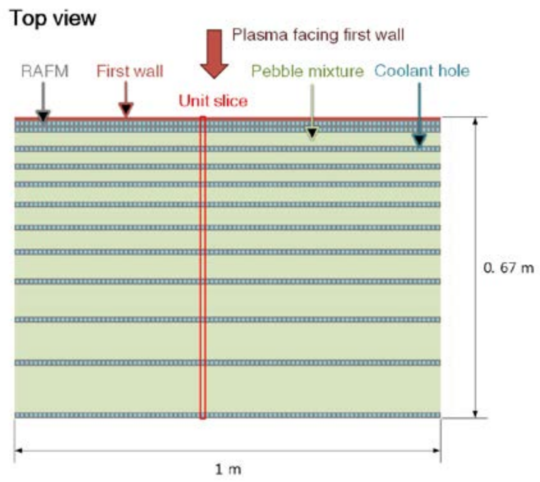


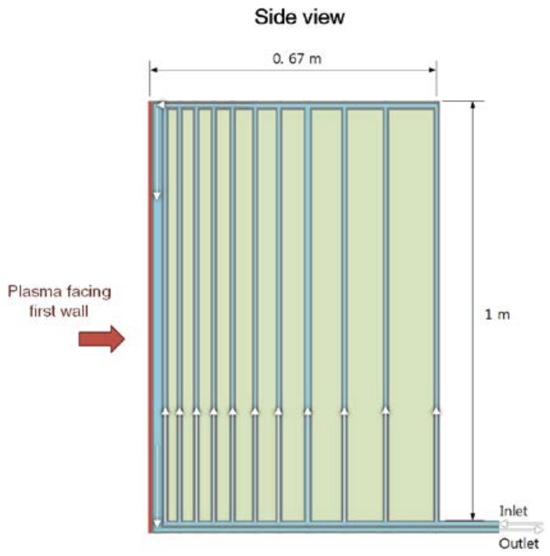
Figure 2. Single sector of K-DEMO blanket



(a) Overall configuration



(b) Top view



(c) Side view

Figure 3. Single module of K-DEMO blanket

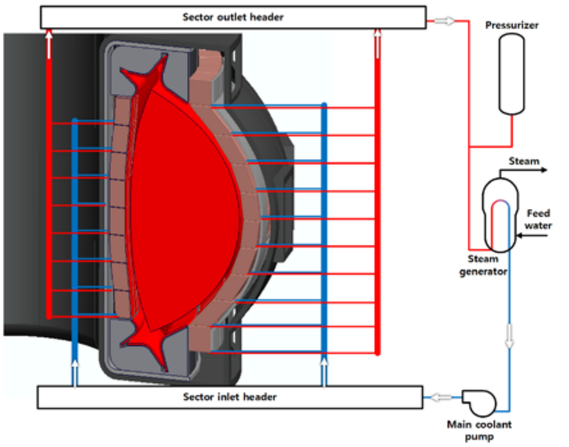


Figure 4. Simplified concept of the blanket cooling system

3. MARS-KS modelling for the blanket thermal analysis

For the proposed blanket system, a computational fluid dynamics (CFD) code analysis was carried out by Park et al. [3] in order to confirm whether the temperature windows of the structural material (250~550°C) and temperature limit (700°C) of the $Be_{12}Ti$ and Li_4SiO_4 pebble bed mixture can be satisfied. The result showed that solid blanket components are operated within their own allowable temperature range.

In the present study, we have proposed the multidimensional analysis of reactor safety (MARS-KS) code [4] as the computational tool for the multi-sector simulation, which has been widely used for the safety analysis of pressurized water reactors, in order to save computational cost and time at the design stage and obtain reliable results for the two-phase flow simulation. The conditions such as properties of heat structures, tungsten, vanadium, RAFM and the mixture of Li_4SiO_4 and $Be_{12}Ti$, were set to be the same as the CFD simulation [3]. The MARS analysis for the blanket model was composed of an inlet time-dependent volume for inlet boundary condition, and inlet branch, 12 pipes, 2 outlet branches and an outlet time-dependent volume for outlet boundary condition. Each coolant pipe was divided into 20 volumes in vertical direction and each volume has a length of 0.05 m as reference. In total, 240 hydrodynamic volumes were used for the coolant channels and 2680 cells for the heat structures such as structural material, breeder and multiplier, as shown in Fig. 5.

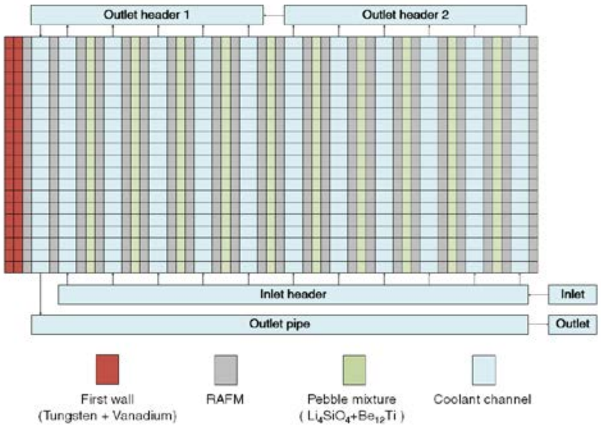


Figure. 5. Single sector of K-DEMO blanket

4. Multi-module simulation methodology using MARS-KS

After the validation of the MARS-KS code for the single blanket thermal analysis carried out by Lee et al. [5], in the present study, a multi-module analysis methodology was proposed. At first, all the blanket modules in a single sector, which comprises 46 blanket modules, were modeled using MARS–KS. The inclination of each module in the poloidal direction was considered and the heat fluxes and heat generation rates in all regions were imposed according to the neutronic analysis results [6]. A unit slice in each module was analyzed with the assumption of toroidal symmetry. The input files of 46 blanket modules were prepared separately, and the common headers of the sector inlet and outlet, which are connected with all the modules, were not considered at this stage. Separate modeling for each module was desired because of the limitation of the number of computational nodes in MARS-KS. In contrast to the CFD codes in which the allowable number of computational meshes is determined by the memory size of the computing machine, the nuclear reactor safety analysis codes such as RELAP5 [7] and the MARS-KS code usually have a restriction on the number of computational meshes imposed by the input file structure. Considering the application of the code for multi-sectors in future, using a single input file is not a practical solution because of the limitation in extending the computational domain to multi-sectors. For this reason, a supervisor program, which can handle the individual blanket module separately using independent input files and make a virtual connection among them through the common headers for the sector inlet and outlet, was developed in the present study.

The concept of a supervisor program is illustrated in Fig. 6; this concept was realized using the dynamic link library (DLL) of the MARS-KS code and its interactive control capability [4]. The interactive control function allows a user to control the input values at every time step using an external program which embeds the DLL files, like for example, the inputs for power, inlet flow rate, etc. In the present study, the supervisor program is given the total mass flow rate that enters the 46 blanket modules, and it distributes the flow rate for each module. At the beginning of the simulation, the program distributes the total flow rate equally to each blanket module. Subsequently, the 46 independent DLL files run the input files prepared for each blanket modules and calculate the pressure drops between the inlet and outlet. Since all blanket modules are connected to the common headers for the sector inlet and outlet, the pressure drops should be identical in all modules. However, as the flow rates are assigned by the supervisor program, they may be different for the modules at the beginning. The pressure drops calculated by MARS-KS DLL files are transferred to the supervisor program before the next time step calculation, and the flow rates are recalculated for each module, during which the pressure drops in all modules are forced to become identical. The pressure drops for the n blanket modules are given by the following equations. For n blanket modules,

$$\Delta P = K_1 \frac{m_1^2}{2\rho_1 A_1^2} = \cdots = K_i \frac{m_i^2}{2\rho_i A_i^2} = \cdots = K_n \frac{m_n^2}{2\rho_n A_n^2} \quad (1)$$

where ΔP is the pressure drop across the blanket modules, m is the mass flow rate, and K is the pressure loss coefficient which includes both the form loss and frictional pressure drop coefficients. K_i for i-th module is calculated from the previous time step pressure drop value and the mass flow rate as below,

$$K_i = \frac{2\rho_i A_i^2 \Delta P_i}{m_i^2} \quad (2)$$

At the same time, the sum of the new time step mass flow rates should be equal to the total mass flow rate for the mass conservation. Thus, the following equation should be satisfied,

$$m_{total} = m_1 + \cdots + m_n \quad (3)$$

Finally, the program calculates the new time step mass flow rate for each module as below and the values are transferred to MARS-KS DLL files as the boundary conditions of the interactive control.

$$m_i = \frac{m_{total}}{\left(\sqrt{\frac{K_i \rho_1}{K_1 \rho_i}} \cdot \frac{A_1}{A_i} \cdots + \sqrt{\frac{K_i \rho_i}{K_i \rho_i}} \cdot \frac{A_i}{A_i} + \cdots \sqrt{\frac{K_i \rho_n}{K_n \rho_i}} \cdot \frac{A_n}{A_i} \right)} \quad (4)$$

With the modified inlet mass flow rates, MARS-KS DLLs calculate the next time step values and transfer the calculated pressure drops to the supervisor program. This procedure is repeated for the whole null transient simulation until a steady-state is achieved and due to this flow redistribution method, the pressure drops in the whole blanket systems can be identical with each other as they are originally connected by sector inlet and outlet headers.

Applying this methodology for the multi-module analysis, the single sector with the 46 blanket modules was analyzed. The total mass flow rate of 561.2 kg/s for the single sector was imposed as the inlet boundary condition and the sector outlet header pressure was maintained at 15.0 MPa as the design parameters. Owing to the high heat capacity of the materials, more than 5000 s of transient simulation time was necessary. Figures 7–10 show the transient behavior of the mass flow rate, pressure drop, and the outlet water temperature in each blanket module. Because of the symmetric configuration of the blanket system with respect to the horizontal axis, the calculation results of four inboard modules (Module IA–Module ID in Fig. 3) and five outboard TF modules (Module OA–Module OE in Fig. 3) in the upper half were displayed in the figures, even though the other modules were also included in the calculation. For the initialization of the simulation, the supervisor code did not control the flow rate until the first 10 s; hence, the flow rate was distributed evenly during the period, as shown in Fig. 7. After this period, the supervisor program started the flow rate control. Therefore, the flow rates of each module started to vary from the constant value. At the same time, the pressure drop between the sector inlet and outlet header converged to a certain value in 20 s as indicated in Fig. 8 and the value was maintained during the remaining period. The outlet water temperature also converges to the target value as shown in Fig. 9. The temperature profile across the first wall to the outmost RAFM at the middle elevation in the steady-state condition is shown in Fig. 10. In the entire region, the RAFM temperatures were within their allowable temperature range of 250–550 ° C, and the mixed breeder and multiplier temperatures were below the design limit of 700 ° C. The temperature distribution of the first wall region of the single sector is shown in Fig. 11; the surface temperature of the plasma facing and the RAFM temperature, cooled by the first wall cooling channel, can be seen in this figure.

By applying this method for multi-module analysis, the 46 blanket modules in the single sector were successfully linked and simulated. This method does not have any limitation in extending the computational domain to multiple sections because each module is independently simulated and the supervisor program virtually connects them. Furthermore, the supervisor program is parallelized by adopting the message passing interface (MPI) system, and therefore, the calculation time can be remarkably reduced by allocating multiple cores. This parallel feature of the present method can be very useful when thermal analysis of a large number of blanket modules is required. However, this approach explicitly calculates the flow rates, making the pressure drops in multiple modules identical, and hence, a very rapid transient may not be accurately simulated. This is a limitation of the proposed approach; therefore, further validation procedure is necessary to ensure that this method can capture the rapid transient behaviors predicted by an integrated simulation of the multiple modules. Meanwhile, the MARS-KS code includes helium as a working fluid and consequently, this approach can be also applied for an efficient simulation of the multiple helium cooled blanket modules.

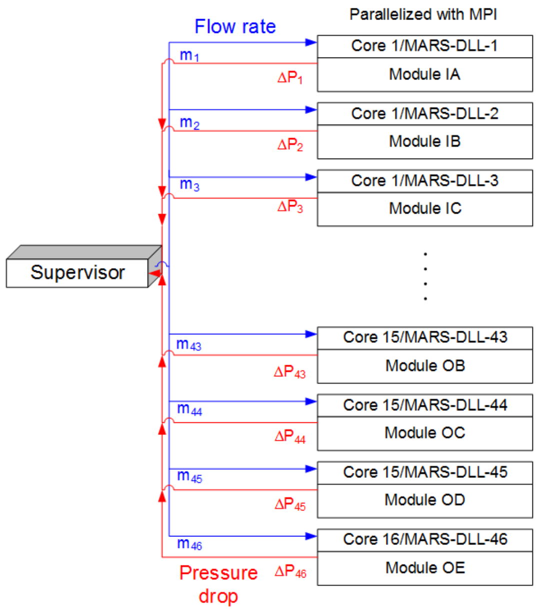


Figure. 6. Concept of the supervisor program for 10 outboard TF modules

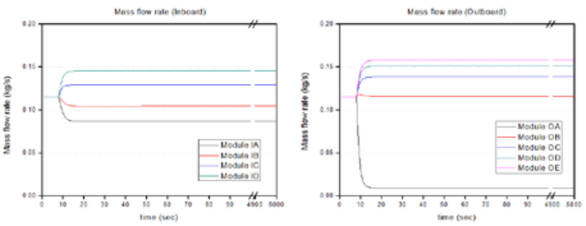


Figure. 7. Calculation result: mass flow rate

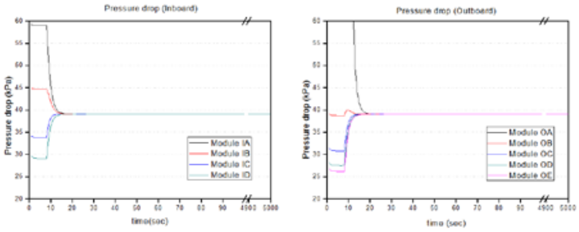


Figure. 8. Calculation result: pressure drop

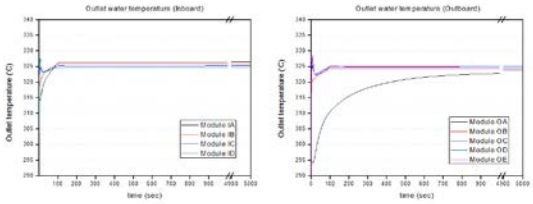


Figure. 9. Calculation result: outlet water temperature

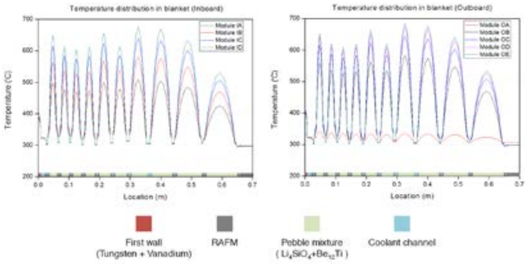


Figure. 10. Temperature distribution from the first wall to the outmost RAFM boundary

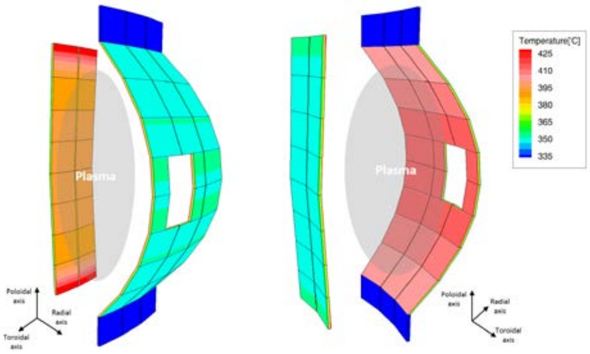


Figure. 11. Temperature distribution of the first wall (Tungsten + Vanadium + RAFM)

5. Conclusions

A thermal-hydraulic analysis code for a nuclear reactor safety, MARS-KS, was applied for thermal analysis of the conceptual design of the K-DEMO breeding blanket. Then, a methodology to simulate multiple blanket modules was proposed, which uses a supervisor program to handle each blanket module individually at first and then distribute the flow rate considering the pressure drop that occurs in each module. For a feasibility test of the proposed methodology, 46 blankets in a sector, which are connected with each other through the common headers for the sector inlet and outlet, were simulated. The calculation results of flow rates, pressure drops, and temperatures showed the validity of the calculation. Because of parallelization using the MPI system, the computational time could be reduced significantly. In future, this methodology will be extended to an efficient simulation of multiple sectors, and further validation for transient simulation will be carried out for more practical applications.

Acknowledgement

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