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Preliminary Analysis for K-DEMO Water Cooled Breeding Blanket Using MARS-KS

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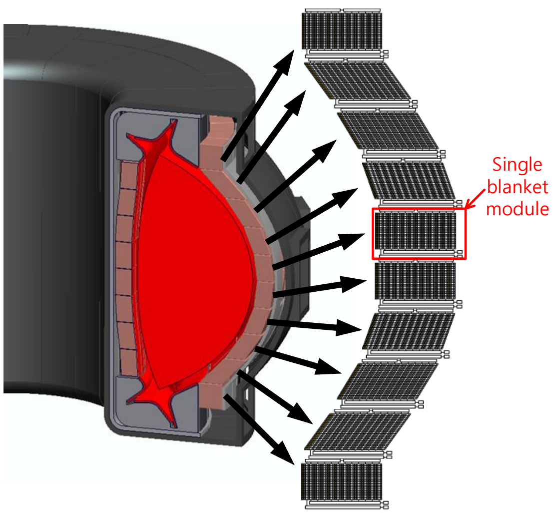
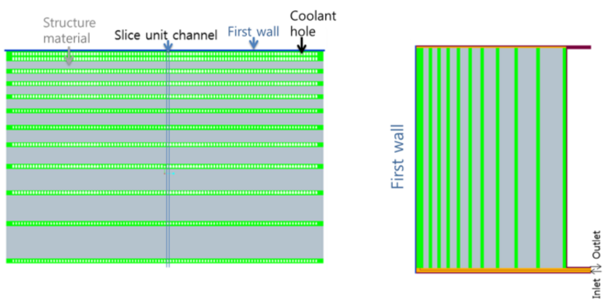
1. Introduction

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 study is aimed to propose design guidelines and requirements for the K-DEMO reactor and it includes the feasibility evaluation of breeding blanket concept. One of the proposed concepts for the blanket model is a multiple-layer-breeding blanket that incorporates multiple layers of breeder and multiplier mixtures, cooling channels, and structural materials parallel to the first wall as illustrated in Fig. 1[3].



(a) Single sector of K-DEMO blanket



(b) Top view and side view of a single blanket module

Fig. 1. Schematic diagram of K-DEMO blanket concept

In the present study, thermal-hydraulic analyses for the blanket concept are being conducted using the Multidimensional Analysis of Reactor Safety (MARS-KS) code [4], which has been used for the safety analysis of a pressurized water reactor. The purposes of the analyses are to verify the applicability of the code for the proposed blanket system, to investigate the departure of nucleate boiling (DNB) occurrence during the normal and transient conditions, and to extend the capability of MARS-KS to the entire blanket system which includes a few hundreds of single blanket modules.

In this paper, the thermal analysis results of the proposed blanket design using the MARS-KS code are presented for the normal operation and an accident condition of a reduced coolant flow rate. Afterwards, the plan for the whole blanket system analysis using MARS-KS is introduced and the result of the first trial for the multiple blanket module analysis is summarized.

2. Water Cooled Blanket Concept for K-DEMO

In the proposed breeder blanket concept for K-DEMO, pressurized water is considered as the coolant and the reduced activation ferritic/martensitic (RAFM) steel is adopted for the structural material. Pebble type Li_4SiO_4 and $Be_{12}Ti$ mixture is considered as the tritium breeder and neutron multiplier in the breeding blanket.

A blanket module has 12 parallel flow channels connected to common headers as show in Fig.1-(b). Pressurized water enters into the lower common header and flows upward along the 11 coolant channels except the first wall cooling channel. The water is collected in the upper common header and flows out of it toward the first wall cooling channel. Then, the water cools the first wall flowing downward and finally, exits the blanket module along the outlet pipe as indicated in Fig. 2. The details of the geometry and dimensions are described in Ref. [3].

With ease of applying the commercial water cooling system at a nuclear fission reactor, the coolant condition of a pressurized water reactor is employed. The operation pressure of the system is 15 MPa, and inlet and outlet temperatures are 290 °C and 330 °C, respectively. The inlet water velocity is set to 4.5m/s. From a neutronics analysis for the geometry, the neutron wall load and the plasma radiation for the first wall heat flux was determined to 2.9MW/m^2 and 0.5MW/m^2, respectively. Heat generation in breeder, multiplier, and RAFM was estimated 3.4MW for the representative model.

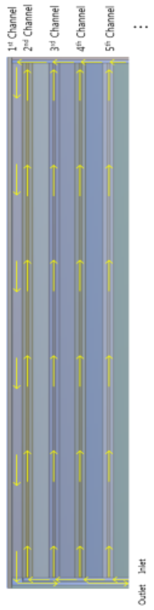


Fig. 2. Flow path in a single blanket module: near the first wall

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 and temperature limits of the $Be_{12}Ti$ and Li_4SiO_4 pebble bed mixture can be satisfied. The result showed that solid blanket components such as mixture of Li_4SiO_4 and $Be_{12}Ti$, and RAFM are operated within their own allowable temperature range, ≤700℃ and ≤550℃, respectively. Water coolant is also operated as satisfying PWR conditions, since mass flow rates of water at each channel are intendedly regulated by optimizing the cross section areas of breeder and multiplier channels.

3. Application of MARS-KS for the Blanket Thermal Analysis

In a water cooled type blanket system, a phase change could occur in the flow channel under normal operation, transient and accident conditions. The boiling can influence the flow distribution and cause flow instability in the blanket system, and accordingly, it is not desired for the normal operation condition. Furthermore, if the heat flux from the structure to the coolant is higher than the critical heat flux (CHF), the heat transfer can be suddenly deteriorated by the departure of nucleate boiling and the temperature of the structure can soar in a very short time resulting in structural damage of the blanket system. Therefore, the two-phase flow analysis is necessary in order to investigate the DNB occurrence and the transient behavior of the system under abnormal conditions.

Even though a CFD analysis has advantages in predicting local temperature and local flow filed in detail, it is unable to give information about two-phase phenomena, such as boiling and DNB occurrence. Moreover, a CFD simulation for the entire system of the fusion blanket requires vast computational cost and time. Consequently, MARS-KS, a thermal-hydraulic analysis code developed for best-estimate analyses of light water reactors, was applied for the blanket analysis. The MARS-KS code has been applied for the nuclear safety analysis under various types of the transient and accident conditions and its capability for the transient two-phase flow simulation has been validated sufficiently. However, since some important closure laws in the code for the prediction of the heat transfer and flow distribution in the system rely on the empirical correlations, the applicability of the code for the present blanket system needs to be confirmed before it is used for the analysis of the system. This being so, the blanket system was modelled using MARS-KS and the calculation results were compared with the CFD prediction.

The conditions of the analysis model were determined to be the same as the CFD calculation conditions. The properties of heat structures, tungsten, vanadium, RAFM and the mixture of Li_4SiO_4 and $Be_{12}Ti$, were also set to be the same as the CFD simulation. The blanket model for the MARS analysis was composed of an inlet time-dependent volume for inlet boundary condition, an inlet branch, 12 pipes, 2 outlet branches and an outlet time-dependent volume for outlet boundary condition. Each pipe for coolant channel was divided into 20 volumes in the vertical direction and each volume has a length of 0.046 m. Since every solid material in the blanket generates heat, 13 heat structures were modeled. The type of geometry for the heat structures was set to be rectangular. Each heat structure was divided into 20 parts axially and divided according to the materials of the structure laterally, as shown in Fig. 3. In total, 240 hydrodynamic volumes were used for the coolant channels and 2,680 cells for the heat structures such as structural material, breeder and multiplier. Unlike CFD simulation, the flow channels were modelled in one-dimension and the heat transfer coefficient correlation of Dittus-Boelter [5] was applied for the wall boundary condition.

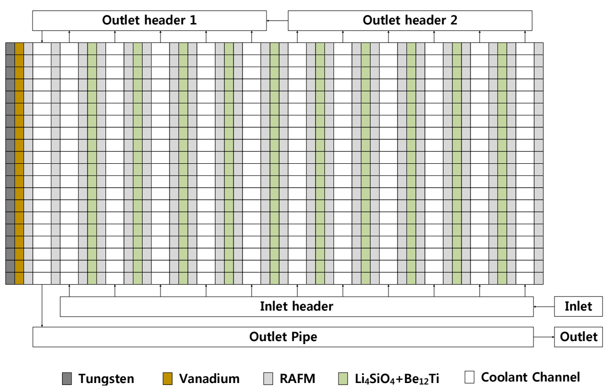


Fig. 3. MARS-KS nodalization for a single blanket module

At first, a reference calculation was performed under a steady-state normal operation condition. It was aimed to validate that MARS can reproduce consistent thermal-hydraulic behaviors with the CFD calculation. The temperature calculation results along a lateral line from the first wall to the outmost RAFM at the middle elevation were compared with CFD prediction as shown in Fig. 4.

The CFD prediction and MARS calculation results showed reasonably good agreement and the maximum difference of peak temperature was 11.5℃ with 1.3% error at the second Li_4SiO_4 and $Be_{12}Ti$ mixture region. This discrepancy might be caused by simplification of the boundary between the heat structure and the coolant. Since MARS-KS models the heat structure using one-dimensional heat conduction equation, the rectangular boundary geometry needs to be modified to a flat surface. In this simplification procedure, the MARS-KS model can lose information of the realistic geometry and modification of the boundary surface area in the MARS modeling is required in order to improve the prediction capability. Despite of this discrepancy, the overall thermal-hydraulic behavior in the suggested blanket system was well reproduced and it was concluded that the blanket modelling using MARS-KS was carried out appropriately.

Afterwards, in order to show the applicability of MARS-KS for a transient or accident condition, a transient simulation for a conceptual problem was carried out. It was postulated that the blanket system underwent the flow rate reduction transient by a pump failure and the flow rate was reduced to the half of the normal operation condition. Fig. 5 indicates the temperature comparison results under the normal operation condition and the reduced flow condition at the top elevation of the blanket. As the flow is reduced, the overall temperature of the blanket is increased. Although the flow is reduced by half, the peak temperatures of heat structures were maintained lower than 700℃, which is the temperature limit of the Li_4SiO_4 and $Be_{12}Ti$ mixture.

With increasing temperature of the coolant, phase change was observed at the 1st, 4th and 8th channels as plotted in Fig. 6. Since the flow direction of the 1st channel is opposed to the other channels, the void fraction in it decreased along the elevation. The void fraction inside the coolant channel increased up to 9%, but the calculation results showed that the nucleate boiling was maintained and the critical heat flux was not exceeded. Owing to this, the heat transfer coefficient between the structure and the coolant remained sufficiently high and the insignificant structure temperature increase was observed.

As described in this example problem simulation, MARS-KS has the capability for the prediction of transient and accident conditions in the proposed blanket module. In the future, this code will be applied to simulate various abnormal conditions which need to be considered for the design, such as anticipated transients and design based accidents.

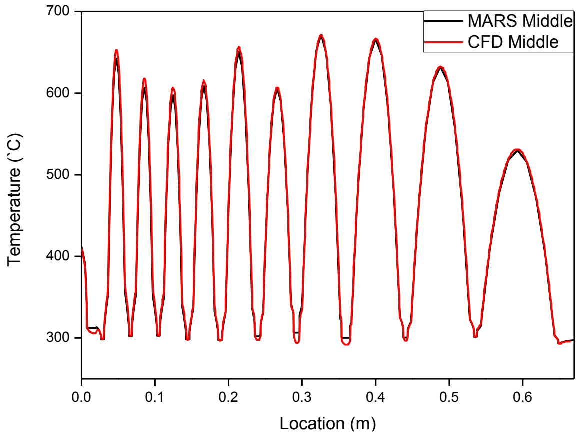


Fig. 4. Comparison results of blanket module temperature profile: MARS-KS vs. CFD

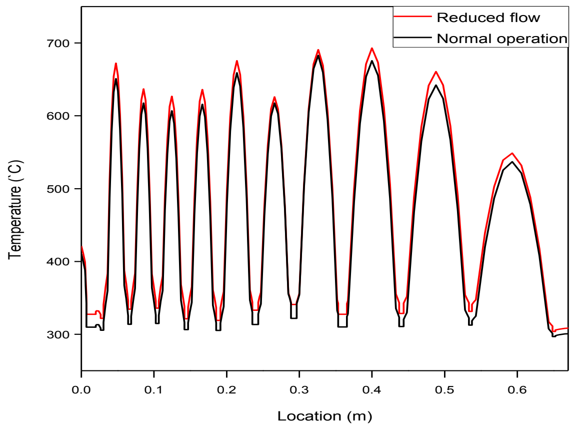


Fig. 5. Comparison results of blanket module temperature profile between normal operation condition and reduced flow condition

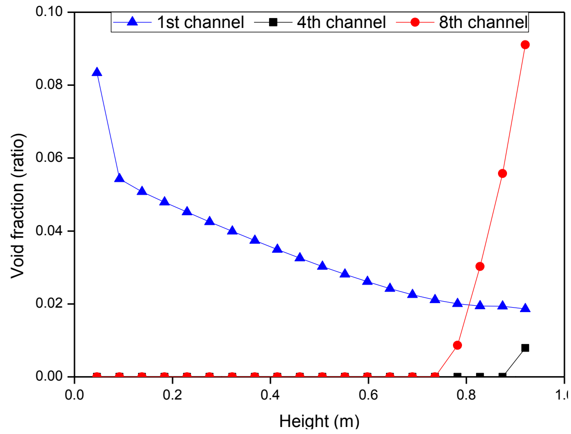


Fig. 6. Void fraction profiles in the coolant channels

4. Multiple Blanket Module Simulation

From the analysis for a single blanket module, it was shown that MARS-KS can be used effectively for the thermal hydraulic analysis of the blanket system including the transient analysis. For more practical application of the code for the blanket system, not only a single module simulation, but the entire system of the blanket has to be analyzed. While a CFD analysis for the entire system of blanket can consume a great deal of computational cost and time, MARS-KS is able to model the entire blanket system by simplifying the geometry in one-dimension and provide the entire system behaviors with much less number of computational cells compared with the CFD analysis. For this reason, MARS-KS was selected for the entire system analysis tool of the blanket and Fig. 7 shows the conceptual diagram for a single sector analysis which comprises 10 blanket modules.

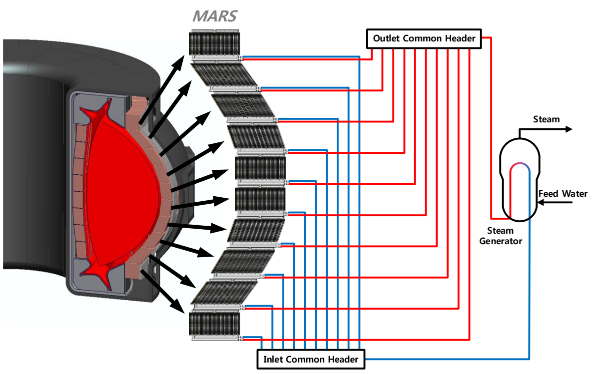


Fig. 7. Conceptual diagram for the analysis of the entire blanket system

However, in the current version of the MARS-KS code, there is the limitation of the computational cells that it can deal with and, therefore, the extension of MARS-KS capability is required for the entire blanket system modeling. In the present study, a methodology for the multiple blanket module analysis was proposed and its feasibility was tested by simulating two blanket modules.

For the feasibility test, the following example problem was defined: The two blanket modules have the same geometry but different heat flux and heat generation rate as illustrated in Fig. 8. Module-1 has much higher heat generation rate and with the heat boundary conditions, a nucleate boiling occurs in the blanket module. By the boiling occurrence, the pressure drop increases and then, it is expected to have lower flow rate than the other if the two blanket modules are connected to the single inlet and outlet common headers.

At first, the two blanket modules were modelled independently for this example problem analysis. Instead of the stand-alone version of MARS-KS, the dynamic linked library (DLL) version of the code was applied, and then, the supervisor code, which was developed in the present study, ran the two independent models of the blanket modules. At the beginning, equal mass flow rates (0.2 kg/s for each) were imposed to the both modules. With the mass flow rates, the MARS-KS calculated the pressure drops across each blanket module. Owing to the boiling in the Module-1 blanket, it has higher pressure drop than the other. Since the two modules are connected with the inlet and outlet common headers, they should have same pressure drops across the system and from the procedures drawn in Fig. 9, the flow rates can be adjusted explicitly.

The pressure loss coefficients (K_1 and K_2) for the given inlet velocities can be evaluated as follows;

$$K_1 = \frac{2\Delta P_1}{\rho V_{1,old}^2},$$
$$K_2 = \frac{2\Delta P_2}{\rho V_{2,old}^2}, \quad (1)$$

where ΔP: pressure drop,
ρ: water density,
V_{old}: water velocity in the previous time step.

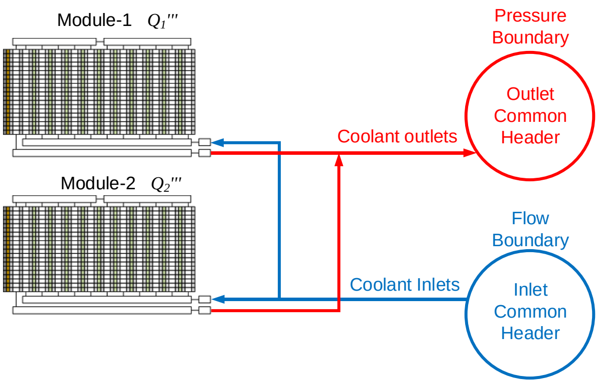


Fig. 8. Example problem for multiple blanket simulation

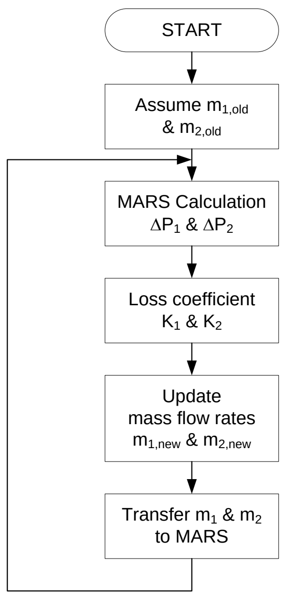


Fig. 9. Procedure for the flow rate determination

For the next time step, the flow rates for each module need to equalize the pressure drops in the two blanket modules, and therefore,

$$\Delta P_1 = \Delta P_2 = \frac{K_1}{2}\rho V_{1,new}^2 = \frac{K_2}{2}\rho V_{2,new}^2, \quad (2)$$

where V_{new}: water velocity in the new time step.

This results in the following relation between the inlet velocities at each module,

$$V_{2,new} = \sqrt{\frac{K_1}{K_2}} V_{1,new}. \quad (3)$$

The two inlet velocities should satisfy the mass conservation equation, and then,

$$\dot{m}_{total} = \dot{m}_1 + \dot{m}_2 = \rho V_1 A_1 + \rho V_2 A_2 = \rho V_1 \left(A_1 + A_2 \sqrt{\frac{K_1}{K_2}} \right), \quad (4)$$

where $\dot{m}$: mass flow rate.

Finally, the inlet velocities of the two modules can be evaluated with the pressure loss coefficients and the inlet velocities of the previous time step,

$$V_{1,new} = \frac{\dot{m}_{total}}{\rho \left(A_1 + A_2 \sqrt{\frac{K_1}{K_2}} \right)} = \frac{A_1 V_{1,old} + A_2 V_{2,old}}{\left(A_1 + A_2 \sqrt{\frac{K_1}{K_2}} \right)}$$

$$V_{2,new} = \frac{A_1 V_{1,old} + A_2 V_{2,old}}{\left(A_1 \sqrt{\frac{K_2}{K_1}} + A_2 \right)}. \quad (5)$$

Since the DLL version of MARS-KS allows the modification of the inlet boundary at every time step, this adjustment of the inlet velocity can be transferred to the two DLL files of MARS-KS code by the supervisor program as the boundary conditions.

Fig. 10 shows the calculation results of the mass flow rates at the inlets of the blanket modules. Due to the higher heat generation rate in Module-1, the higher pressure drop appeared as expected and then, decrease of the mass flow rate was followed. When the steady state was achieved, the flow rates in Module-1 and Module-2 were 0.1936 kg/s and 0.2064 kg/s, respectively, and the pressure drop difference between the two modules was less than 10^{-6} Pa.

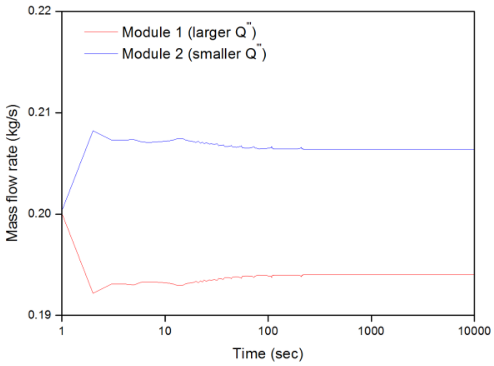


Fig. 10. Mass flow rates in the multiple blanket module simulation

From this analysis for two blanket module, it was concluded that this explicit common header modelling using the MARS-KS DLL can be successfully applied for the multiple blanket module simulation. In the future, the present method will be extended to the single sector simulation which incorporates 10 blanket modules and, thereafter, the code will be used for the design optimization and the transient/accident analysis of the entire blanket system of K-DEMO.

5. Conclusion

In the present study, thermal-hydraulic analyses for the blanket concept were conducted using the MARS-KS code for a single blanket module. By comparing the MARS calculation results with the CFD analysis results, it was found that MARS-KS can be applied for the blanket thermal analysis with less number of computational meshes. Moreover, due to its capability on the two-phase flow analysis, it can be used for the transient or accident simulation where a phase change may be resulted in. In the future, the MARS-KS code will be applied for the anticipated transient and design based accident analyses. The investigation of the DNB occurrence during the normal and transient conditions will be of special interest of the analysis using it.

After that, a methodology to simulate the entire blanket system was proposed by using the DLL version of MARS-KS. A supervisor program, which controls the multiple DLL files, was developed for the common header modelling. The program explicitly determines the flow rates of each module which can equalize the pressure drops in them and transfers the flow rates to each DLL file as inlet flow rate boundary conditions. The methodology was applied for the two blanket module simulation and its performance was successfully validated. The multiple blanket module analysis method will be extended to the entire system analysis following the present work.

Acknowledgement

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