Development of Thermal-hydraulic Analysis Methodology for Multi-module Breeding Blankets in K-DEMO

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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 study 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.

In this paper, the purpose of the analyses is to extend the capability of MARS-KS to the entire blanket system which includes a few hundreds of single blanket modules. Afterwards, the plan for the whole blanket system analysis using MARS-KS is introduced and the result of the multiple blanket module analysis is summarized.

2. Design concept of water-cooled breeding blanket

One of the proposed concepts for the blanket model is a water-cooled multiple-layer-breeding blanket, which incorporates multiple layers of breeder and multiplier mixtures, cooling channels, and structural materials parallel to the first wall as illustrated in Figs. 1 and 2 [3]. Fig. 1 depicts the in-vessel component segmentation (22.5°) and Fig. 2 introduces the configuration of a single blanket module that locates the center of the single sector. The blanket modules in the conceptual design of K-DEMO are segmented into 16 sectors along the toroidal direction and each sector has 16 inboard and 30 outboard modules. 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. 3.

A single blanket module has 12 parallel flow channels connected to common headers as shown in side view of Fig.2-(b). Pressurized water (15 MPa) 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 downward into the first wall cooling channel and finally, exits the blanket module along the outlet pipe. Inlet and outlet temperatures are 290℃ and 325℃~330℃, respectively. Also, the flow rate for each module needs to be optimized in order to achieve the target temperature, 325℃~330℃ at the exit of the outlet sector header. From the balance between the heat load on each module and rise of the fluid temperature, the optimum flow rates were determined and an orifice plate was installed in each manifold branch for the optimum flow distribution.

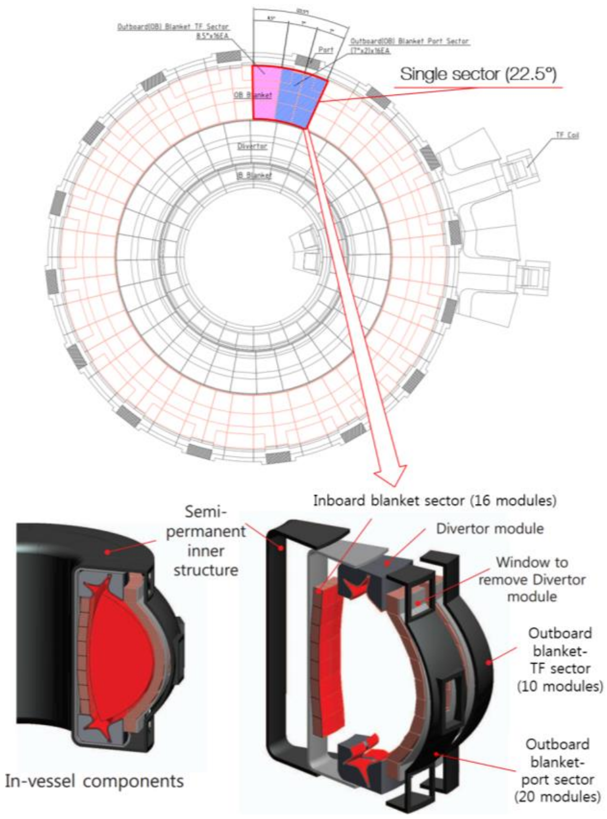
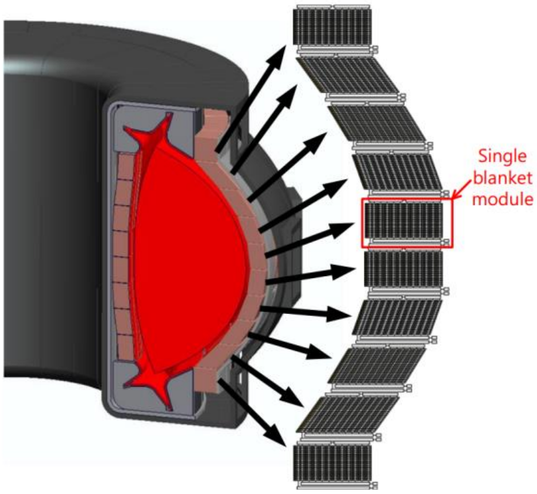
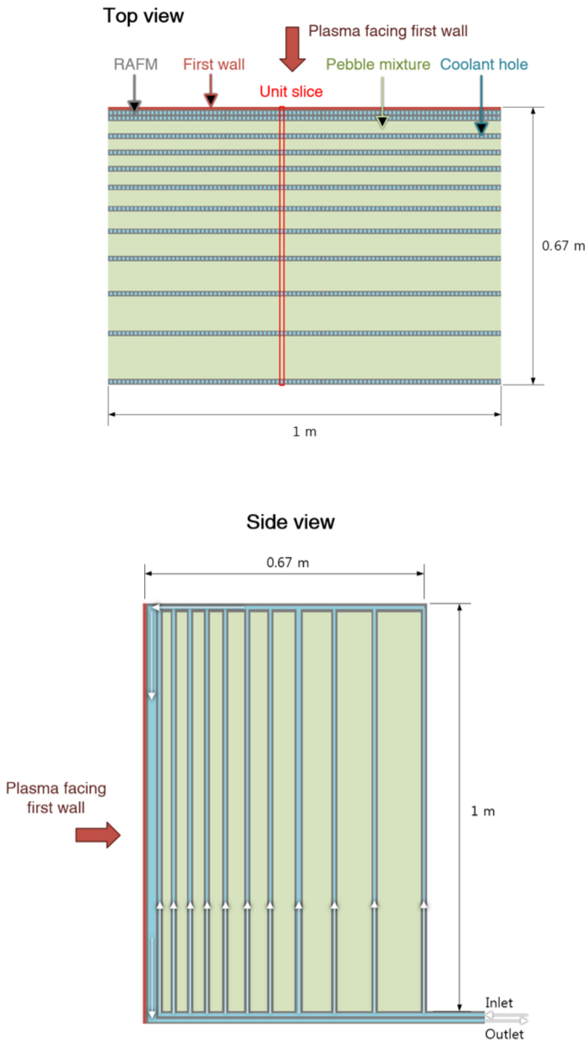


Fig. 1 Single sector of K-DEMO outboard blanket



(a) Overall configuration



(b) Top view and side view
Fig. 2 Single module of K-DEMO blanket

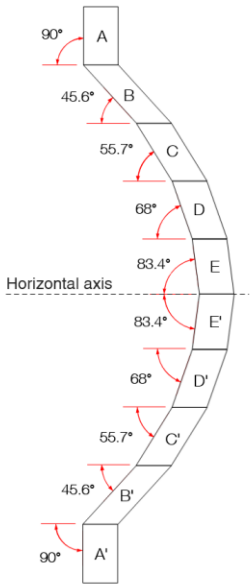


Fig. 3 Single sector of K-DEMO blanket

3. MARS-KS modelling for the single 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℃) and temperature limit (700℃) 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, 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 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. 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. 4. 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 convective wall boundary condition.

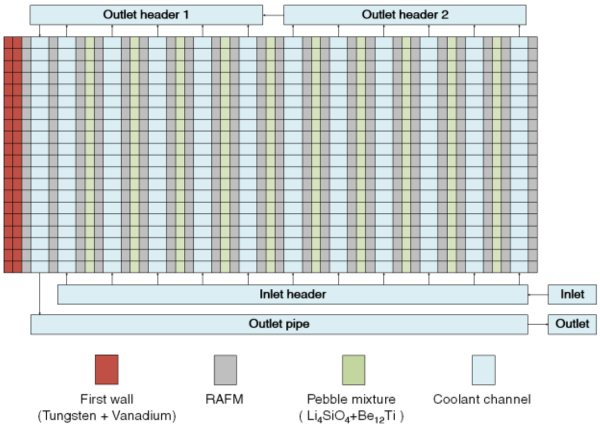


Fig. 4 Single sector of K-DEMO blanket

4. Multiple blanket module analysis methodology using MARS-KS

After the modelling of MARS-KS for the single blanket thermal analysis, a multi-module analysis methodology was proposed. At first, all the blanket modules in a single outboard TF sector, which is comprised of 10 blanket modules, were modelled using MARS–KS as shown in Fig. 5. 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 summarized in Table 1. Similar to the previous chapter, a unit slice in each module was analyzed with the toroidal symmetric assumption. The input files of 10 blanket modules were prepared separately and the inlet and outlet sector common headers, which are connected with the 10 modules, were not considered at this stage. The reason for the separate modelling for each module is due to the limitation of the computational node numbers of MARS-KS. Consequently, 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 inlet and outlet sector common headers, was developed in the present study.

The concept of the supervisor program was illustrated in Fig. 6 and it was realized by using the Dynamic Linked Library (DLL) of MARS-KS and its interactive control capability [6]. The interactive control function offers a user to control the input values at every time step using an external program which embeds the DLL files, for example, the power, inlet flow rate, etc. In the present study, the supervisor program is given the total mass flow rate that enters into the 10 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. And then, 10 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 inlet and outlet sector common headers, the pressure drops should be identical in all modules. But the flow rates are assigned by the supervisor program and then they may be different from each other 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 it recalculates the flow rates for each module which enforce the pressure drops in the all modules to be identical with each other based on the following equations. For n blanket modules,

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

where ΔP : pressure drop,
m : mass flow rate
K : pressure loss coefficient
and K_i for i-th module is calculated from the previous time step pressure drop value and the mass flow rate as below,

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

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,

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

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.

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

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 inlet and outlet headers.

Appling this methodology for the multi-module analysis, the outboard TF sector with 10 blanket modules were analyzed. The total mass flow rate for the single TF sector of 120.3 kg/s was imposed as the inlet boundary condition and the outlet header pressure was maintained at 15.0 MPa as the design parameters. Due to high heat capacity of the materials, longer than 5000 seconds of transient simulation was necessary. Figures 7~9 shows the transient behavior of the pressure drop, mass flow rate, and the outlet water temperature in each blanket module. Thanks to the symmetric configuration of the blanket system with respect to the horizontal axis, the calculation results of 5 modules in the upper half (Module A ~ Module E in Fig. 3) were displayed even though the other modules (Module A' ~ Module E' in Fig. 3) were included in the calculation.

For the initialization of the simulation, the supervisor code did not control the flow rate until the first 10 seconds and accordingly, the flow rate was distributed evenly during the period. After that, 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 inlet and outlet header converged to a certain value in 20 seconds and the value was maintained for the remained transient. The outlet water temperature also converges to the target value. When the steady-state was achieved, the temperature profile across the first wall to the outmost RAFM at the middle elevation was plotted in Fig. 10. In the whole region, the RAFM temperature are within their temperature allowable rage, 250℃~550℃ and the mixed breeder and multiplier temperature are below its design limit, 700℃.

Applying this method for multi-module analysis, 10 blanket modules in the outboard TF sector were successfully linked and simulated. This method does not contain 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) and therefore, the calculation time can be remarkably reduced by allocating multiple cores. In the present calculation, the parallelization with 10 cores reduced the whole computational time by almost 1/10 and the efficiency of the parallel computation (E_p), of which definition is below, was 0.97.

$$E_p = \frac{T_1}{pT_p} \qquad (5)$$

where T_1 is the execution time with a single processor, p the number of processors, and T_p is the execution time with multiple processors. Except for the flow rate and pressure transfers at each time step, there is no more communication and synchronization among the processors and good parallel efficiency could be achieved. This parallel feature of the present method can be very useful when thermal analysis of the entire blanket system is required.

However, this approach explicitly calculates the flow rates which make the pressure drops in multiple modules identical and a very rapid transient may not be accurately simulated. It can be the limitation of the proposed approach and therefore, further validation procedure is necessary to ensure that this method can capture the transient behaviors predicted by an integrated simulation of the multiple modules. Meanwhile, MARS-KS 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.

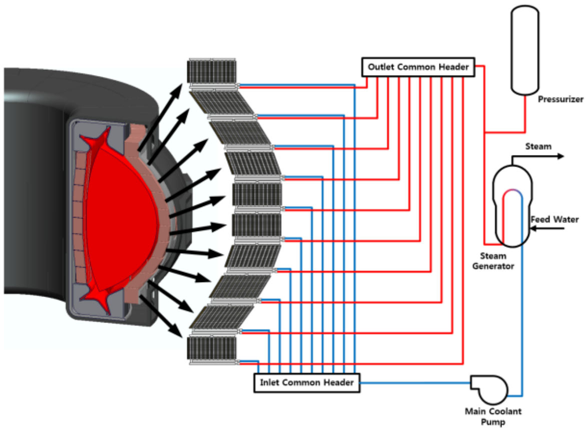


Fig. 5 Simplified concept of blanket cooling system

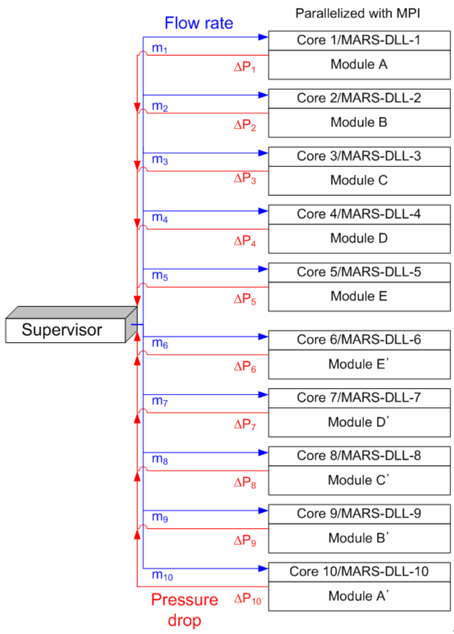


Fig. 6 Concept of the supervisor program for 10 outboard TF modules

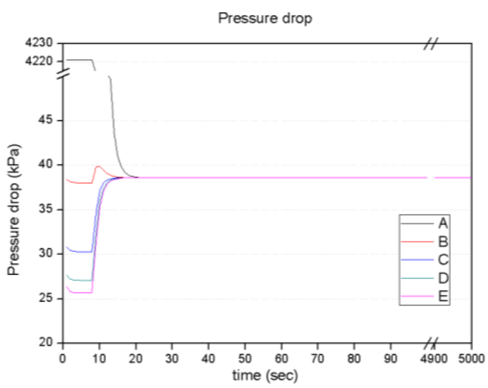


Fig. 7 Calculation result: pressure drop

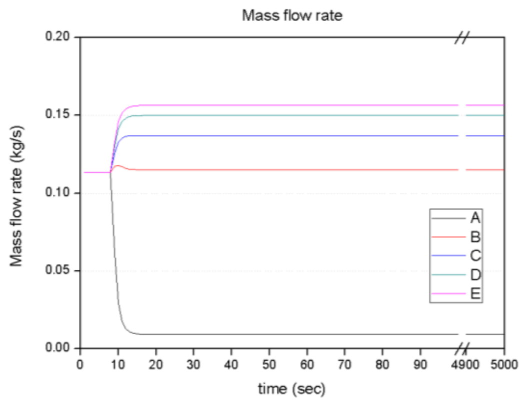


Fig. 8 Calculation result: mass flow rate

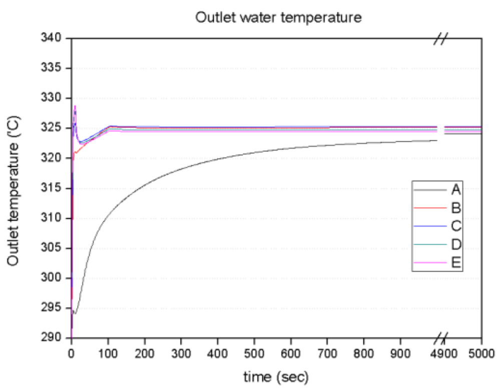


Fig. 9 Calculation result: outlet water temperature

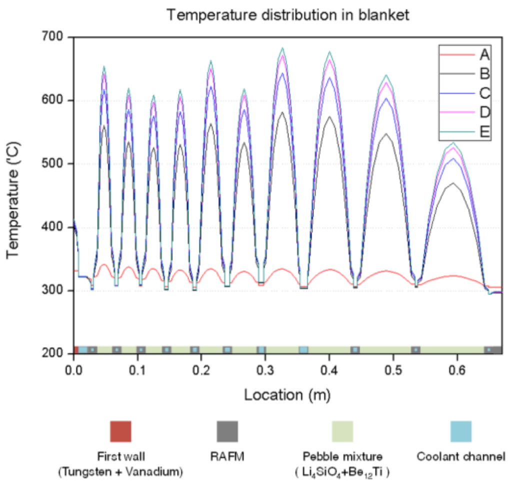


Fig. 10 Temperature distribution from the first wall to the outmost RAFM boundary

Table 1: First wall heat flux and volumetric heat generation rate in blanket modules

First wall heat flux [kW/m²]	0.0	423.0	426.3	445.1	455.0
Volumetric heat generation rate [kW/m³]					
Layer \ Module	A, A'	B, B'	C, C'	D, D'	E, E'
Tungsten	2840.0	29678.2	36494.3	39476.3	40896.3
Vanadium	777.6	8125.5	9991.6	10808.0	11196.8
1st cooling channel	1038.8	10854.9	13347.9	14438.6	14958.0
2nd cooling channel	1038.8	10854.9	13347.9	14438.6	14958.0
1st $Li_4SiO_4+Be_{12}Ti$	1054.6	11020.8	13551.8	14659.2	15186.5
3rd cooling channel	946.3	9888.8	12159.9	13153.5	13626.6
2nd $Li_4SiO_4+Be_{12}Ti$	930.9	9728.2	11962.4	12939.9	13405.4
4th cooling channel	825.5	8626.6	10607.8	11474.6	11887.3
3rd $Li_4SiO_4+Be_{12}Ti$	784.6	8198.9	10081.9	10905.7	11298.0
5th cooling channel	689.8	7207.9	8863.4	9587.6	9932.5
4th $Li_4SiO_4+Be_{12}Ti$	629.9	6582.4	8094.2	8755.6	9070.5
6th cooling channel	550.0	5747.6	7067.6	7645.1	7920.1
5th $Li_4SiO_4+Be_{12}Ti$	474.1	4954.8	6092.8	6590.6	6827.7
7th cooling channel	409.3	4276.8	5259.0	5688.7	5893.4
6th $Li_4SiO_4+Be_{12}Ti$	360.5	3767.6	4632.9	5011.4	5191.7
8th cooling channel	307.4	3212.8	3950.7	4273.5	4427.2
7th $Li_4SiO_4+Be_{12}Ti$	243.9	2548.6	3133.9	3390.0	3512.0
9th cooling channel	217.6	2274.0	2796.3	3024.7	3133.5
8th $Li_4SiO_4+Be_{12}Ti$	153.1	1600.2	1967.8	2128.5	2205.1
10th cooling channel	132.8	1387.3	1706.0	1845.4	1911.7
9th $Li_4SiO_4+Be_{12}Ti$	94.0	981.8	1207.3	1306.0	1353.0
11th cooling channel	78.7	822.0	1010.8	1093.3	1132.7
10th $Li_4SiO_4+Be_{12}Ti$	42.4	442.8	544.5	589.0	610.2
12th cooling channel	30.9	323.3	397.6	430.1	445.6

5. Conclusions

A thermal-hydraulic analysis code for a nuclear reactor safety, MARS-KS, was applied for the conceptual design of the K-DEMO breeding blanket thermal analysis. 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 pressure drops arises in each module. For a feasibility test of the proposed methodology, 10 outboard blankets in a toroidal field sector were simulated, which are connected with each other through the inlet and outlet common headers. The calculation results of flow rates, pressure drops, and temperatures showed the validity of the calculation and thanks to the parallelization using MPI, almost linear speed-up could be obtained. In the future, this methodology will be extended for an efficient simulation of multiple sectors and further validation for the transient simulation will be carried out for more practical application.

Acknowledgement

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