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Development of thermal-hydraulic analysis methodology for multiple modules of water-cooled breeder blanket in fusion DEMO reactor

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HIGHLIGHTS

- A methodology to simulate the K-DEMO blanket system was proposed.
- The results were compared with the CFD, to verify the prediction capability of MARS.
- 46 Blankets in a single sector in K-DEMO were simulated using MARS-KS.
- Supervisor program was devised to handle each blanket module individually.
- The calculation results showed the flow rates, pressure drops, and temperatures.

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ABSTRACT

According to the conceptual design of the fusion DEMO reactor proposed by the National Fusion Research Institute of Korea, the water-cooled breeding blanket system incorporates a total of 736 blanket modules. The heat flux and neutron wall loading to each blanket module vary along their poloidal direction, and hence, thermal analysis for at least one blanket sector is required to confirm that the temperature limitations of the materials are satisfied in all the blanket modules. The present paper proposes a methodology of thermal analysis for multiple modules of the blanket system using a nuclear reactor thermal-hydraulic analysis code, MARS-KS. In order to overcome the limitations of the code, caused by the restriction on the number of computational nodes, a supervisor program was devised, which handles each blanket module separately at first, and then corrects the flow rate, considering pressure drops that occur in each module. For a feasibility test of the proposed methodology, 46 blankets in a single sector were simulated; the calculation results of the parameters, such as mass flow, pressure drops, and temperature distribution in the multiple blanket modules showed that the multi-module analysis method can be used for efficient thermal-hydraulic analysis of the fusion DEMO reactor.

1. Introduction

Based on the National Fusion Roadmap of Korea [1], a preliminary design concept for the Korean fusion demonstration reactor (K-DEMO) has been proposed by the National Fusion Research Institute (NFRI) [2]. Under this roadmap, a series of research works have been performed in order to establish the foundation for the conceptual design of the 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 depicts the configuration of a single blanket module that is located at the center of the outboard sector.

According to the conceptual design of the K-DEMO reactor, the water-cooled blanket system incorporates a total of 736 blanket modules. 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. These blanket modules are connected with one another through the common headers for the sector inlet and outlet. The heat influx through the plasma facing surface, the heat generation

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Nomenclature

f	geometry factor
h	convective heat transfer coefficient
k	thermal conductivity of RAFM
q''	heat flux
T	temperature
U	overall heat transfer coefficient
ΔP	pressure drop across the modules
A	area of module inlet
m	mass flow rate
K	pressure loss coefficient

Greek letter

δ	thickness of RAFM
ρ	density of water

Subscripts

f	fluid
wall	wall
i	i-th module
n	number of modules for calculation

due to the neutron irradiation, and the geometric configuration of each module vary depending on the module's poloidal location, and therefore, the thermal analysis of the blanket system needs to be carried out for at least one sector, with the assumption of toroidal symmetry during normal operating conditions. If transients or accident conditions need to be considered, such as plasma disruption and vertical displacement event, an asymmetric heat influx condition could occur, and accordingly, multi-sector simulation would be required in order to confirm the integrity of the blanket system under those conditions.

For the proposed blanket system, computational fluid dynamics (CFD) simulation was carried out by Park et al. [3] to confirm whether the temperature windows of the structural material (250–550 °C) and the temperature limit (700 °C) of the $Be_{12}Ti$ and Li_4SiO_4 pebble bed mixture can be satisfied. The results showed that the solid blanket components such as the mixture of Li_4SiO_4, $Be_{12}Ti$, and reduced activation ferritic/martensitic steel (RAFM) operate within their allowable temperature ranges. The CFD simulation was carried out for a single blanket module, which receives the highest heat load among the blanket modules in a single sector, under normal operating conditions. For the single module simulation, approximately 900,000 computational cells were used. If the CFD simulation needs to be extended for multiple-sector simulation, it may require huge computational cost and a very long time. Moreover, in the case of a water-cooled blanket system, two-phase flow may occur under transient and accident conditions; it can cause instability inside the coolant channel, and lead to CHF (critical heat flux) condition, which can result in serious structural damage. However, the prediction capability of the CFD software for the two-phase flow and CHF is not sufficient for it to be used for the system design. These difficulties in the multi-sector simulation using CFD software motivated us to carry out the present work.

In order to save computational cost and time at the design stage and obtain reliable results for the two-phase flow simulation, 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 our previous work [5], to verify the applicability of the code for the blanket system, a thermal-hydraulic analysis had been performed for a single module under normal operating conditions, and the results had been compared with the CFD analysis results. The comparison showed that a reasonable agreement can be obtained between the results as per MARS-KS code and those as per CFD analysis in the prediction of the structure temperatures.

In the present study, the analysis was extended to multiple module analysis, and 46 blanket modules in a single sector were simulated using the code. For this purpose, a supervisor program, which connects the independent blanket modules modeled by the MARS-KS code, was developed for an efficient simulation. This paper presents the conceptual design and the preliminary configuration of the K-DEMO water-cooled blanket system, and the single module simulation results using the MARS-KS code. Then, the proposed methodology for the multi-sector simulation using the code is introduced. Finally, the feasibility test result for the methodology, based on the tests performed with the 46 blankets in the sector, is discussed.

2. Water-cooled blanket concept for K-DEMO

In the proposed breeder blanket concept for K-DEMO, pressurized water is considered as one of the candidates for the coolant, and the reduced activation ferritic/martensitic (RAFM) steel is used as the structural material. A mixture of pebbles of Li_4SiO_4 and $Be_{12}Ti$ is considered as the tritium breeder and neutron multiplier in the breeding blanket. Tungsten is selected as the first wall material. Because it is easy to apply the commercial water cooling system in a nuclear fission reactor, the coolant conditions of a pressurized water reactor is employed. The operating pressure of the system is 15 MPa, and the inlet and outlet temperatures are 290 °C and 325–330 °C, respectively. The blanket modules in the conceptual design of K-DEMO are segmented into 16 sectors along the toroidal direction, with each sector having 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. Fig. 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, as listed in Table 1 [3,6]. 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, as listed in Table 1, and the fluid temperature rise, the optimum flow rates were determined, and an orifice plate was placed 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. 2b. 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 dimensions of a representative slice are indicated in Fig. 5. 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. 2c. Pressurized water enters the lower module header and flows upward along the 11 coolant channels, except along the first wall cooling channel. The water is collected