Nuclear Analysis of Structural Damage and Nuclear Heating on Enhanced K-DEMO Divertor Model

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Abstract. This paper addresses nuclear analysis on the Korean fusion demonstration reactor (K-DEMO) divertor to estimate the overall trend of nuclear heating values and displacement damages. The K-DEMO divertor model was created and converted by the CAD (Pro-EngineerTM) and Monte Carlo Automatic Modeling (MCAM) programs as a 22.5° sector of the tokamak. The Monte Carlo neutron photon transport (MCNP) and ADVANTG codes were used in this calculation with FENDL-2.1 nuclear data library. The calculation results indicate that the highest values appeared on the upper outboard target (OT) area, which means OT is exposed to the highest radiation conditions among the three plasma-facing parts (inboard, central and outboard) in the divertor. Especially, much lower nuclear heating values and displacement damages are indicated on the lower part of OT area than others. These are important results to perform thermal-hydraulic and thermo-mechanical analyses on the divertor and also it is expected that the copper alloy materials may be partially used as a heat sink only at the lower part of OT instead of reduced activation ferritic-martensitic (RAFM) steel due to copper alloy's high thermal conductivity.

1. Introduction

Studies to investigate the feasibility of the divertor system have been proceeding [1] since the pre-conceptual design study on the Korean fusion demonstration reactor (K-DEMO) was initiated in 2012 [2,3]. Previously, nuclear analyses to predict main parameters: neutron wall loading (NWL), tritium breeding ratio (TBR), and nuclear heating, were carried out in an overall K-DEMO model [4]. However, nuclear analyses to examine nuclear responses for individual components such as the divertor were not yet performed.

The divertor is one of the main components and great challenges for a tokamak reactor. Its major function is the handling of the high heat flux, helium, and impurities from the plasma, and also the divertor should be able to endure the large plasma power and high radiation conditions inside the tokamak reactor [5].

Neutronic analyses are an essential part for the divertor design to predict important nuclear reactions such as nuclear heating and displacement damages. Nuclear heating values generated from neutrons and secondary photons in the vicinity of the plasma-facing parts will be used as an essential input for thermal-hydraulic and thermo-mechanical analyses. Displacement damages induced by neutrons cause a material defect in the divertor system. Particularly, accumulated damages in the divertor materials of plasma-facing parts are an important factor to predict its lifetime for maintenance during its operation.

In this paper, the K-DEMO divertor was integrated into a previously developed K-DEMO neutronic analysis model [6]. And then, two important nuclear responses, nuclear heating, and displacement damage for the K-DEMO divertor system were examined using Monte Carlo neutron photon transport code (MCNP) [7] with FENDL-2.1 [8] nuclear data library.

Through these analyses, we estimated the overall trend of nuclear heating values and displacement damages on K-DEMO divertor system in the global model. Also, these estimates will be useful for the further nuclear and thermo-mechanical analyses as a reference.

2. K-DEMO Divertor Model

K-DEMO divertor system adapts the symmetric double-null type with upper and lower 96 modules in the toroidal direction, and vertical maintenance concepts.

Each divertor module is categorized according to its purpose. The plasma-facing parts are made of tungsten armored high heat flux (HHF) units to remove plasma radiation heat and nuclear heating. These parts are consisting of the inboard target (IT), outboard target (OT), and central dome (CD), which are supported by the water cooled reduced activation ferritic-martensitic (RAFM) [9] steel backplate. The cassette part is made of RAFM including water coolant manifolds to cool down plasma-facing parts [1].

The K-DEMO divertor model was created and converted by the CAD (Pro-Engineer™) and Monte Carlo Automatic Modeling (MCAM) programs as a 22.5° sector of tokamak [10].

Divertor system of fusion power reactor has a complex geometry. However, a simplified K-DEMO divertor neutronic analysis model (see FIG. 1) was applied for following calculations as its detail design is still in progress. This simplification is considered barely affected the nuclear analysis results since plasma-facing geometries of simplified and detail models were exactly same.

TABLE I shows material compositions on K-DEMO divertor system [4]. Models without homogenization of materials are important due to the strongly various nuclear responses according to different materials. The plasma-facing and cassette parts with tungsten, RAFM, and water were individually modeled without any material homogenization. Then, these models were subdivided into several parts in order to have detail nuclear responds for the following Monte Caro simulation.

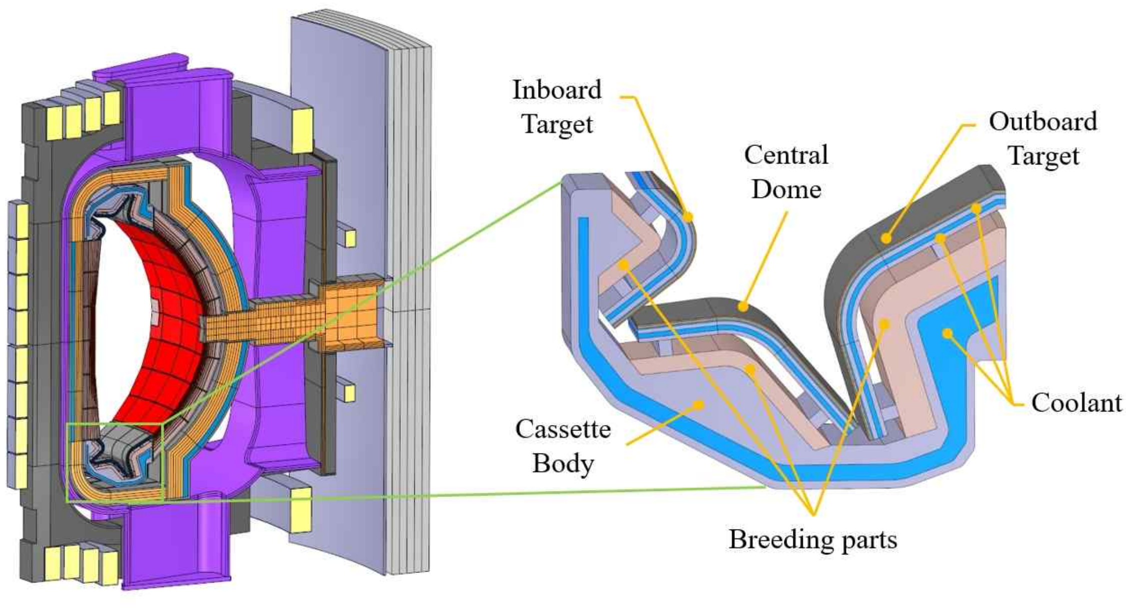

FIG. 1. A configuration of 22.5° K-DEMO neutronic analysis model (left) and a concept of the divertor module (right).

TABLE I: MATERIAL COMPOSITION OF THE K-DEMO DIVERTOR.

Components	**Material Composition**
Monoblocks	Tungsten
Monoblock Backplate	RAFM
Coolant	Water
Cassette Body	RAFM
Breeding Zone:	Mixture of Li_4SiO_4 15% and $Be_{12}Ti$ 85%, ^6Li enrichment: 90%

3. MCNP Calculation

The MCNP code was used on the displacement damage calculation using the simple and accurate analysis methods [11], and nuclear heating calculations with FENDL-2.1 nuclear data library. The average statistical error rates on the nuclear heating and displacement damage calculations for the MCNP runs were below ~5%. Errors less than 10% are generally reliable [7, 12].

The fusion neutron emission probability data were applied on the plasma region [4] and then, 2,200 MW of K-DEMO fusion power was normalized in the following calculations. To reduce computing time and effort due to the iterative calculations, the ADVANTG code for Monte Carlo simulations to generate variance reduction parameters was used in this calculation [13].

3.1.Nuclear Heating Calculation

Nuclear heating values generated from neutrons and secondary photons on the K-DEMO divertor system were indicated in FIG. 2. The total nuclear heating values on plasma-facing parts of the 96 divertor modules were 172.3, 85.2, 50.6, 98.8 MW in OT, CD, IT and Cassette Body areas, respectively (see TABLE II).

Nuclear heating values are strongly dependent on the relative locations in the divertor model to the neutron source in the plasma. A relatively high percentage of nuclear heating values (28%) in a single module was appeared on the upper OT area, whereas the lower part of the OT area showed relatively lower nuclear heating values (138 kW) than others.

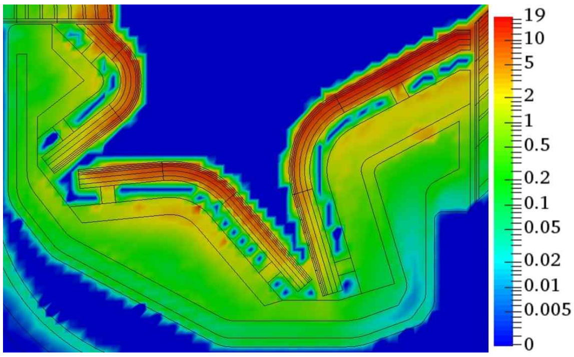

FIG. 2. Map of nuclear heating rate (W/cm^3) for the divertor region in K-DEMO.

TABLE II: NUCLEAR HEATING ON THE K-DEMO DIVERTOR

Components	Single Module (kW)	96 Modules (MW)
OT (Upper/Mid/Lower)	1794 (1183/473/138)	172.2 (113.6/45.4/13.2)
CD (Outer/Mid/Inner)	888 (291/366/231)	85.2 (27.9/35.1/22.2)
IT (Upper/Mid/Lower)	527 (163/259/105)	50.6 (15.6/24.9/10.1)
Cassette Body	1029	98.8
Total	4236	406.7

Diverters also play an important role as the shielding along with divertor shields to protect TF coils behind them. The nuclear heating calculation on 16 TF coils of K-DEMO global model already confirmed that the K-DEMO in-vessel components and shielding concepts could maintain the nuclear heating in superconducting magnets below the reasonable level (14 kW) by earlier studies [4, 6]. In TABLE II, the total nuclear heating on 96 divertor modules was 406.7 MW, which was almost the same with the earlier studies.

3.2.Displacement Damage Calculation

Neutrons from the plasma generate the material damages expressed through displacement per atom per full power year of operation (dpa/fpy). Generally, displacement damage is strongly dependent on the threshold displacement energy [14] of materials, and neutron fluxes in specific tally volumes.

In FIG. 3, the maximum damages are indicated in the RAFM heat sink material of upper OT area with a value of 10.9 dpa/fpy. Although RAFM was further away from the plasma, the displacement damage on RAFM (10.9 dpa/fpy) was higher than tungsten (2.6 dpa/fpy). This is due to the lower threshold energy of RAFM than tungsten (RAFM ~40 eV, W 90 eV).

In general, copper alloy materials are not considered as a heat sink for K-DEMO divertor system despite its high thermal conductivity than RAFM since they cause reusable and radioactive waste problems.

However, we tried the copper material as a heat sink at the lower OT area because this area showed relatively lower displacement damage rates with RAFM material than others. The heat sink of lower OT area was subdivided into 8 tally volumes to compare detail displacement damages using RAFM and copper materials (see FIG. 3).

In FIG. 4, the displacement damages in RAFM and copper materials were gradually increased in the upper direction. Also, the copper material shows ~56% higher displacement damage rates than RAFM material. However, the copper material shows much lower displacement damage rates comparing with other parts (see FIG. 3) since it is less exposed to the neutrons in the plasma.

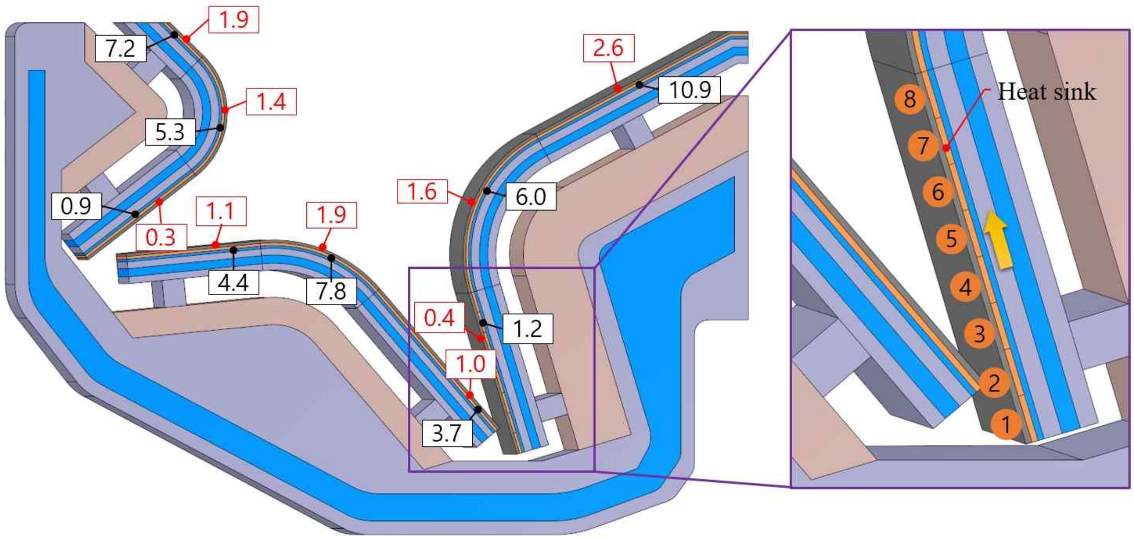

FIG. 3. The maximum displacement damage on tungsten armors (red) and RAFM heat sinks (black) of K-DEMO divertor system (left) and a detail view of lower OT area (right).

4. Discussion and Conclusion

This study investigated that nuclear heating values and the displacement damages on the three plasma-facing parts of K-DEMO divertor. The highest values appeared on the upper OT area, which means OT is exposed to the highest radiation conditions among the three plasma-facing parts in the divertor.

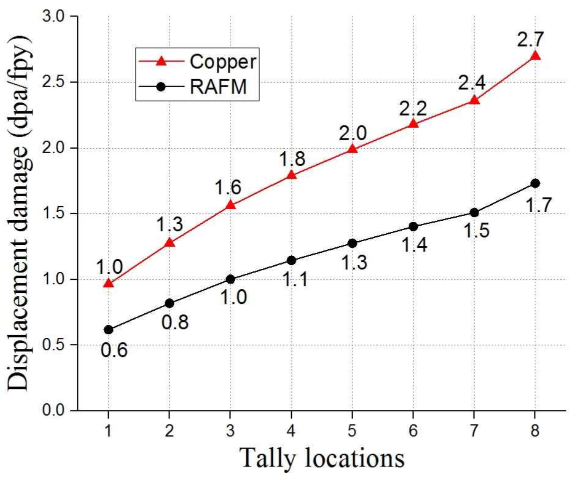

FIG. 4. Comparison of calculated displacement damage rates between copper and RAFM materials in the heat sink of lower OT area.

We found much lower nuclear heating and displacement damages are indicated on the lower part of OT area than others. These are important results to perform thermal-hydraulic and thermo-mechanical analyses on the divertor and also it is expected that the copper alloy materials may be partially used as a heat sink only at the lower part of OT instead of RAFM material due to its high thermal conductivity.

But careful attention should be paid to use copper alloy materials as the heat sink due to its activation characteristics. Therefore, further study of activation calculations on K-DEMO divertor using copper alloy materials as the heat sink will be conducted in the future.

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