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Thermo-hydraulic optimization study for a high heat flux unit of the K-DEMO divertor target

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ABSTRACT

Exhaust the very demanding incident heat flux of about 10 ~ 20 MW/m^2 concentrated on the narrow area of the divertor target is one of the most challenging requirements in the fusion DEMO reactor. The divertor has to remove the plasma power within allowable temperature ranges of the comprising materials such as armor, heat sink, and coolant. To satisfy the requirement, the optimized design of the divertor is significant as well as the selection of the comprising materials. In the K-DEMO (Korean fusion demonstration reactor), the target peak heat flux of 10 MW/m^2 was set in the steady-state operation and a water-cooled divertor concept employing the tungsten monoblock has been primarily considered. RAFM (reduced activation ferritic martensitic) steel has been considered the primary candidate as heat sink material and CuCrZr has been the second best plan in the K-DEMO divertor. The purpose of this study is to derive optimum design for two design options: RAFM and CuCrZr. To carry out the design optimization based on thermo-hydraulic and statistical analyses, input parameters such as top thickness and lateral thickness of monoblock and thickness of coolant tube and output parameters such as maximum temperatures of monoblock and coolant tube are defined. In the parameter correlation analysis, regression equations defining the relation between the input and output parameters were derived with statistical values. Finally, the optimized designs for CuCrZr and RAFM models satisfying objectives and constraints were derived by the response surfaces optimization. The optimized designs applying the derived design parameters showed the designs satisfy the thermal requirement.

1. Introduction

The divertor is one of the most important and challenging in-vessel components in the fusion reactor. The main functions of the divertor are to exhaust power and to control particles. Especially, to exhaust power is a critical role in DEMO reactors compared to other experimental fusion reactors. In general, it is estimated that almost half of the plasma power would be treated in the divertor [1]. The power should be converted to electricity for efficiency in the DEMO. However, cooling down about half of the plasma power in the divertor area is an extremely severe requirement [2]. Moreover, the heat flux caused by the plasma locally concentrates on the narrow section of the divertor target. The peak value of the heat flux of DEMO devices is estimated over 10 MW/m^2 in the steady-state operation [3,4]. In the transient state such as the edge localized mode, the peak heat flux applied on the divertor target for hundreds of μs is much higher than in steady-state operation. The divertor target has to not only withstand the extreme heat load but also guarantee the high duty cycle lifetime for years. Therefore, various types of advanced approaches such as X-divertor [5], snowflake divertor [6], and super X-divertor [7] have been explored to reduce and spread the peak heat flux. In addition, the activation of materials caused by the neutron irradiation and the plasma wall interaction are difficult challenges in the DEMO divertor [8].

In Korea, the conceptual study of a DEMO reactor has been carried out since 2012. The present in-vessel components of the K-DEMO (Korea fusion demonstration reactor) have been designed for 2200 MW of fusion power [2,9]. The plasma contains ~560 MW of heating power comprised of ~440 MW of α -particle heating and ~120 MW of external auxiliary heating. The major and minor radiuses of the plasma are 6.8 m and 2.1 m, respectively. About 10 MW/m^2 of the peak heat flux is set to the outboard divertor target considering ~85% radiation of the edge plasma in the steady-state operation [2]. To remove the plasma power, a water-cooled divertor concept employing tungsten monoblock has been primarily considered in the K-DEMO [2,9]. Tungsten is chosen as an armor material due to its remarkable material properties at high temperature. RAFM (reduced activation ferritic martensitic) steel and CuCrZr have been considered the primary candidate and the second best plan as heat sink material in the K-DEMO

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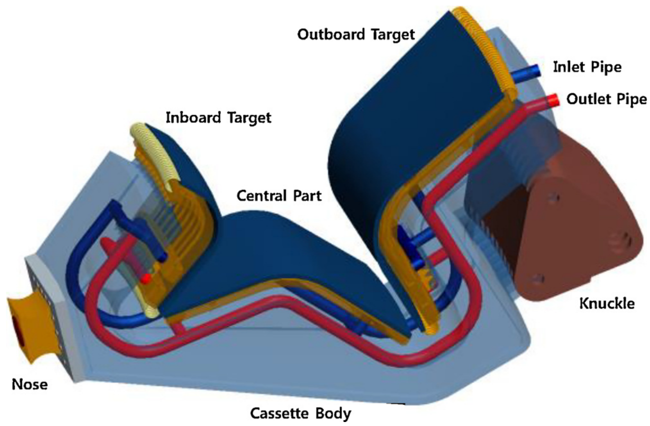

Fig. 1. Overview of the K-DEMO divertor module.

divertor, respectively.

The aim of this study is to derive the optimum design for an HHF (high heat flux) unit of the K-DEMO divertor target by carrying out the thermo-hydraulic and statistical analyses. Firstly, the design parameter correlation was accomplished to define the relations between input and output parameters. Based on the correlation, DOE (design of experiment) was done to derive the response surfaces. The response surfaces provide the expected values of the output parameters, everywhere in the range of selected input parameters without performing CFD (computational fluid dynamics) analyses. Based on the response surfaces, the optimum designs were derived from two models employing RAFM steel and CuCrZr.

2. Concepts of the K-DEMO divertor

The key feature of the K-DEMO configuration is that the divertor system has upper and lower divertors with symmetry [2]. The upper and lower divertors are subdivided into 32 modules, respectively. A divertor module consists of an inboard target, an outboard target, a central part, a cassette body, and connecting components such as nose and knuckle as shown in Fig. 1. The divertor target geometry is designed to tilt the targets at 10° and 11.5° for outboard and inboard targets, respectively, against the corresponding separatrix field lines to accommodate the peak heat flux of 10 MW/m^2. The inlet and outlet cooling manifolds for each module deliver coolant to the outboard target, the central part, and the inboard target in parallel. The monoblock design with HHF units similar to the ITER divertor has been applied to the inboard and outboard targets (see Fig. 2). A central part has a different concept because the heat flux is much lower. Instead of the HHF units, grooved wide tungsten plates are bonded to the heat sink with laminated interlayer in order to avoid surface cracking.

The first step of designing divertor target is the selection of the coolant because it determines the overall concept and the efficiency of the reactor. Helium, supercritical water, and pressurized water have been discussed as potential candidates for the coolant in DEMO reactors [3]. Helium was pushed back on the priority because He-cooling is not enough to cool down the heat load within the operating temperature range of the heat sink in DEMO devices [4]. Supercritical water was also excluded in the K-DEMO because it can cause serious corrosion problem. Today, pressurized water appears to be the most promising choice for the main coolant of the K-DEMO mainly due to the accumulated experience in power plants. The PWR (pressurized water reactor) condition has been taken into account in the K-DEMO [9].

Plasma facing material requires high thermal resistance, high strength, low tritium inventory, and low sputtering yield since the material directly interface with the edge plasma. Tungsten has been considered as the most promising plasma facing material up to now in DEMO devices. However, the brittleness below DBTT (ductile-brittle transition temperature), oxidation, and transmutation under neutron irradiation were estimated as the drawbacks of tungsten. Recently, the crack propagation of tungsten on the plasma facing surface was reported in the high heat flux test, 20 MW/m^2 [10]. The root cause of the defect was the cyclic excesses of the recrystallization temperature of tungsten [11]. In order to prevent the defect, the functional material based on the tungsten matrix has been studied [12].

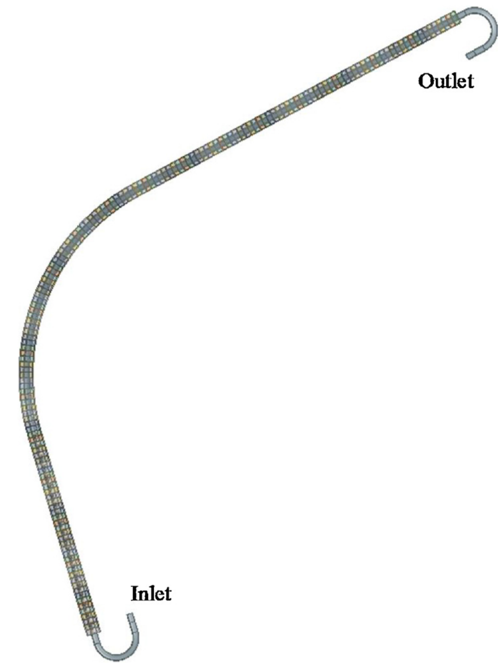

Fig. 2. Configuration of an HHF unit in outboard the divertor target.

The coolant tube used as the heat sink should effectively transfer the heat loads to the coolant. Thus, high thermal conductivity is the most important material property for a good heat sink material. High yield/ultimate strength and elastic modulus at high temperature, and corrosion resistance are also required since the heat sink has to play a role as a structural material. In that sense, CuCrZr is the most attractive material for the heat sink since it has a high thermal conductivity of 357 W/m°·C at room temperature [4]. However, CuCrZr could be a high level activated material under the neutron irradiation in the DEMO condition. Moreover, the operating temperature window of CuCrZr is relatively narrow, 200 ~ 300 °C [4]. Due to the narrow operating temperature range, the coolant of PWR condition (15 MPa, the coolant inlet temperature ~290 °C, ΔT ~ 40 °C) cannot be applied, so that it is not proper to generate electricity. Therefore, RAFM steel has been considered as another candidate for the heat sink in the DEMO to make up for the weak points of CuCrZr. RAFM steel has been selected because it is a low activated material. Furthermore, the PWR condition can be applied to RAFM steel because it has a wide and high operating temperature window of 300 ~ 550 °C [13]. In addition, the mechanical properties of RAFM steel such as elastic modulus, yield strength, and the ultimate strength are better than those of CuCrZr. However, RAFM steel is not an effective material in terms of heat transfer because of its poor thermal conductivity of 26 W/m·°C at room temperature. The major thermal and mechanical properties of CuCrZr and RAFM are summarized in Table 1.

3. Design parameters for an HHF unit of the K-DEMO

CHF (critical heat flux) was estimated before carrying out the CFD analysis, in order to ascertain if the peak heat flu x 10 MW/m^2 is able to cause the transient boiling. To calculate the CHF of the circular tube with a swirl tape, the modified TONG's formula was employed [14,15].