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Conceptual Design of Fixed Tungsten Target for Spallation Neutron Source: A Replication Study

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1. Introduction

At the Korea Multi-purpose Accelerator Complex (KOMAC) of Korea Atomic Energy Research Institute (KAERI), in order to maximize the use of 100-MeV proton accelerator, which is large national research facility, a conceptual design is made for a spallation neutron source based on a high-power proton accelerator [1]. The objective of this study was to obtain the development direction of high-power metal targets. To achieve this, a target model was secured by performing target modeling that replicated the shape of stationary tungsten targets in Spallation Neutron Source (SNS). Subsequently, thermal-hydraulic and thermal-structural analysis were simulated under identical conditions to compare the results and identify potential vulnerabilities in the model. In future high-power target studies, the target performance will be upgraded by improving the currently identified vulnerabilities, and stable spallation neutron source operation will be secured by target design and production technology. Here, we describe the fixed tungsten target study of the spallation neutron target at KOMAC.

2. Modeling of Fixed Tungsten Target

For the conceptual design of the fixed metal target, we referred to the fixed tungsten target previously studied for the Spallation Neutron Source - Second Target system (SNS-STS) in 2015 [2]. SNS's target was designed with a proton beam power of 500 kW and 1.3 GeV, which differs from KOMAC's specifications. However, in order to ensure the reliability of the high-power target conceptual design and thermal structure analysis, the design study was conducted utilizing the SNS proton beam specification and compared with the SNS-STS analysis results.

The fixed tungsten target modeling was designed based on the 8.6 cm * 3.5cm proton beam to enable the comparison of analysis results under identical conditions [3]. The target is a cuboidal piece of tungsten, with a tantalum cladding to prevent corrosion due to direct contact with the coolant. The target has a fixed small gap to allow the coolant to pass through, and including the gap, the total length of the target is approximately 300 mm with respect to the center axis of the proton beam. The coolant flows horizontally across each target from three supply channels on one side to a single outlet channel on the opposite side. The overall geometry of the conceptualized fixed metal target is shown in Fig. 1.

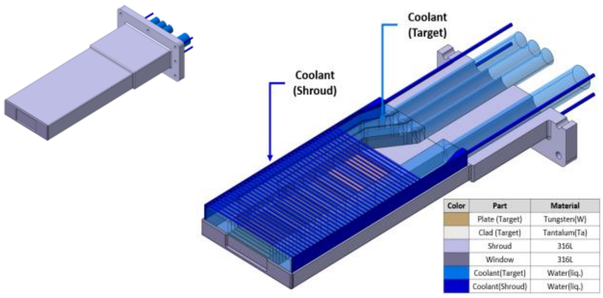

Fig. 1. Full geometry of the fixed metal target

Simplifications were made to reduce analysis time in areas that did not affect the analysis. A stationary metal target consists of a tungsten target, a tantalum cladding, a stainless-steel (316L) shroud and flange, and a target window. The coolant flows independently of each other in two separate areas, one to cool the target and the other to cool the shroud. The coolant zones are shown in Fig. 1.

3. Initial Boundary Condition

The properties of the tungsten (W), tantalum (Ta), and stainless-steel (316L) used in the target are summarized in Table Ⅰ. The properties of stainless-steel (316L) were taken at 50℃. And water was chosen as the cooling fluid and its properties were adjusted at 3.5 bar.

	Molar mass (g/mol)	Density (kg/m^3)	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)
W	183.84	19,250	128.3	174.9
Ta	180.95	16,600	139	57.2
SS316L	180.9	7,919	485	14.7

Table I: Metal material properties for thermal-hydraulic analysis [4]

In order to perform thermal-hydraulic analysis, thermal boundary conditions are required. The heat load due to the proton beam can be calculated using MCNP6, and it is used as the thermal boundary condition. However, in this study, the anticipated heat load values were calculated by applying the same proton beam conditions to the target for comparison with the results from SNS. The heat load values applied to each target are summarized in Fig. 2.

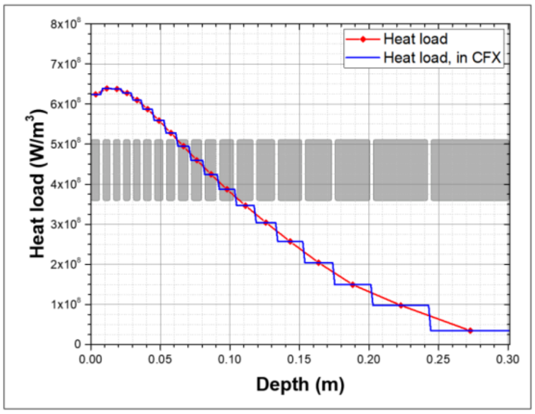

Fig. 2. The heat load values according to the thickness of the tungsten plate [5]

A single-phase analysis was conducted using the turbulent model (k-ε) [6] with a reference pressure of 3.5 bar, and an initial cooling water temperature of 43 °C was used. Water flow rate entering between the 19 target was 13.564 kg/s, and this flow rate value was applied to the inlet area of the target. For the shroud, the water flow rate of 0.1 kg/s was assumed and applied to the shroud cooling water inlet area.

4. Analysis

4.1. Thermal-hydraulic Analysis

Examining the temperature distribution in the cross section of the target center axis shown in Fig. 3, the temperature is found to be high in the center of the 15th to 19th tungsten plates, and particularly, the maximum temperature of 160.9°C was observed in the 18th tungsten plate. The reason for this is estimated to be that although the tungsten plate receives a high amount of heat, it is not sufficiently cooled due to the reduced cooling effect caused by the thickness of the target. At the corresponding point, the maximum temperature of 131.5°C was observed in the tantalum cladding. Among the stainless steel-made shroud, frame, and target window, the maximum temperature of 130.2°C occurred in the shroud.

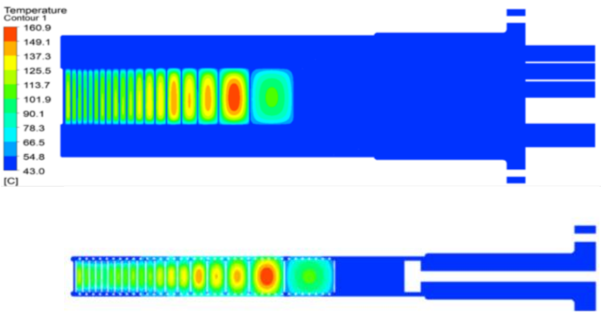

Fig. 3 Temperature distribution on fixed metal target

The temperature of the cooling water between the tungsten plates was about 46 °C on average, which increased by approximately 3 °C compared to the inlet temperature. The average flow velocity was 9.9 m/s. The average temperature at the outlet of the target cooling water was 46.8 °C, which increased by 3.8 °C from the initial cooling water temperature. The flow velocity increased by approximately 2.4 m/s compared to the inlet due to the structure of the cooling water accumulating and exiting at the outlet. Additionally, the required average pressure drop for the cooling water to reach the outlet from the inlet was calculated to be about 1.9 bar.

4.2. Thermal-structural Analysis

To conduct a structural analysis of composite loads, the weight, the internal pressure, and the results of thermal-hydraulic analysis were used as boundary conditions for this analysis.

	Elastic Modulus (GPa)	Poisson's ratio	Thermal expansion (/K)	Yield stress (MPa)
W	398	0.28	4.3E-6	1,360
Ta	188	0.35	6.3E-6	705
SS316L	200	0.3	15.3E-6	190

Table II: Metal material properties for thermal-structural analysis [4]

The maximum stress occurred in the tantalum cladding and shroud areas. In the case of the tantalum cladding, the maximum stress of the target did not exceed the yield stress of tantalum at 298.5 MPa. However, for the Shroud, it was confirmed to exceed the yield stress of SS316L at 254.9 MPa. The reason for the maximum stress was found to be the stress concentration caused by the corner area where the shroud contacts the target. The maximum deformation was less than 0.1 mm in all areas. As a result, it was found that it was structurally safe except for the part where the yield stress exceeded.

4.3. Comparing Analysis Results

The temperature distribution at the center of the target calculated in this study was compared with the thermal-hydraulic analysis results presented in the SNS-STS technical report, and the comparison was summarized in Fig. 4. There were similar parts in the temperature distribution on the front of the target, but the temperature trend changed from the 19th target, and the KOMAC's thermal-hydraulic analysis results were interpreted to be 20 ~ 30°C lower than those presented in the SNS-STS technical report. The average flow velocity, the average flow rate of cooling water in the target and Reynolds number were generally similar to those in the technical report. However, the surface heat flux of the target differed by about 40%, and the pressure drop also showed a difference of about 0.4 bar. In particular, the heat transfer coefficient differed by about 48%.

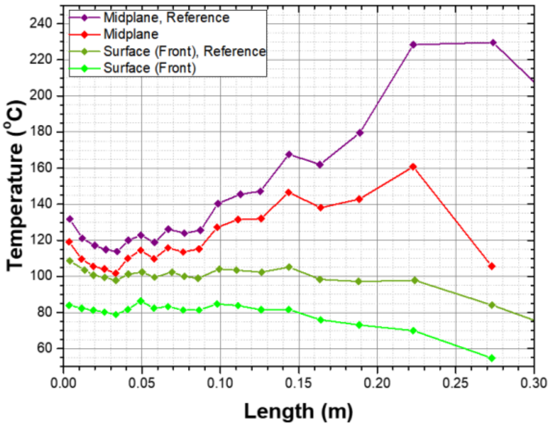

Fig. 4 Comparing the results of thermal-hydraulic analysis

5. Summary

In this study, we designed stationary solid metal target. The shape of the target was modeled, and thermal-hydraulic and thermal-structural analysis was performed to secure the basic data of the target. The weaknesses of the target identified through this study will be improved and the target design will be refined.

Acknowledgments

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