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Thermal Evaluation for Safety Test Model of SNF Dry Storage Module using Scaling Characteristics

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1. Introduction

Korea Hydro & Nuclear Power (KHNP) is developing a dry storage module for the on-site dry storage of spent nuclear fuel. This dry storage module is designed similarly to the vertical dry storage facility (MACSTOR) of the Wolsong Nuclear Power Plant. It has already demonstrated its safety in various aspects such as storage, shielding, and structural integrity. However, with the transition from pressurized water reactor (PWR) spent fuel to pressurized heavy water reactor (PHWR) spent fuel, several differences can arise.

One significant difference lies in the thermal aspect. In the case of PWR spent fuel, the design decay heat is around 150 kW, while the dry storage module is designed for approximately 240 kW, leading to an increase of about 60% in heat generation. To validate the thermal performance of the dry storage module, a scaled test model was designed, and this research was conducted to verify it using Computational Fluid Dynamics (CFD) codes.

2. Methods and Results

To simulate the heat transfer phenomenon of the prototype model using a scaled-down model, it is necessary to utilize similarity laws for scaling analysis and validation. Scaling analysis using the heat transfer similarity law can be applied to conduction and radiation heat transfer analysis, while the scaling ratio obtained from the fluid flow similarity law can be applied to convective heat transfer analysis. Since the dry storage module involves both heat conduction and fluid flow, a scaling analysis considering both heat conduction and fluid flow using similarity laws is necessary for thermal testing using the scaled-down model. In this study, three heat transfer modes were analyzed for scaling between the prototype and scaled-down models: convective heat transfer through air ducts from the decay heat of spent nuclear fuel, conductive heat transfer through the main concrete structure of the module, and combined convective and conductive heat transfer through air ducts and the module's structure. These analyses were performed to derive the scaling ratio between the prototype and scaled-down models. In the combined mode of convection, conduction, and radiation heat transfer, the decay heat of spent nuclear fuel is emitted through convective heat transfer via air ducts in the dry storage module, radiative heat transfer through the module's structure, conductive heat transfer through the module's structure walls, and convective and radiative heat transfer from the surface of the module's structure. Assuming that the environmental temperature of the dry storage module remains constant in this complex heat transfer mode, the scaling ratio between the prototype and scaled-down models was determined.

For the three heat transfer modes, CFD analysis was conducted for the prototype model and a 1/2 scaled-down model, considering both the prototype model and scaled-down model variables (temperature, velocity, mass flow rate) to analytically demonstrate the reliability of the scaling and similarity of the scaled-down model compared to the prototype model. The thermal analysis model for the scaled-down model is structured the same as the prototype model. A 3D, 1/2 symmetric, finite volume model was created for the thermal analysis of the dry storage module under normal operating conditions of spent nuclear fuel. The schematic representation of this model is shown in Figure 1. In the complex heat transfer mode that considers convective heat transfer through air ducts, conductive heat transfer through the module's structure, and radiative and convective heat transfer from the surface of the module's structure, the thermal analysis for the scaled-down model was conducted with correction factors. The total decay heat of spent nuclear fuel in the scaled-down model was considered as 44.985 kW, which is 0.208 times the decay heat per module (216 kW) in the prototype model. The temperature distribution results for the 1/2 scaled-down model are shown in Figure 2, and differences in key variables are presented in Table 1.

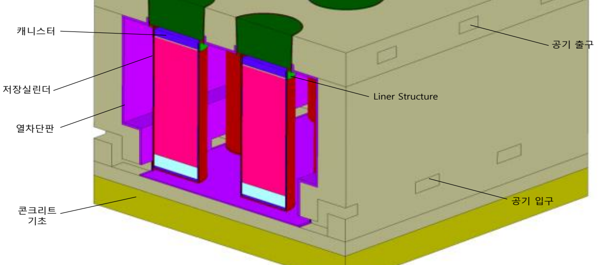

Fig. 1. Calculation Domain of Dry Storage Module

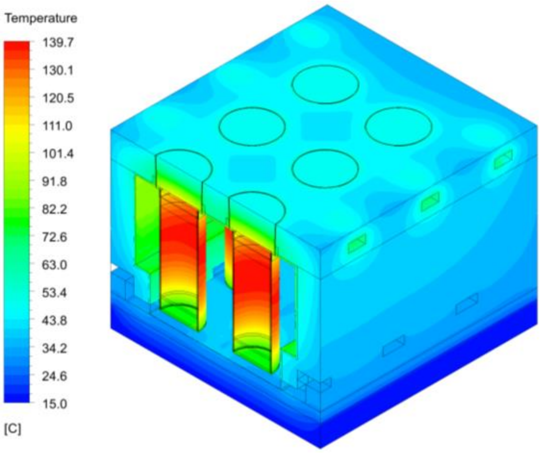

Fig.2. Flow Recovery Ratio against Height

Table.1. CFD Test Results of prototype and Scaled Models.

Item	prototype	Scaled
Max. Concrete Temp. [℃]	77.2	73.2
Max. Isolated plate Temp. [℃]	102.4	92.5
Max. Cylinder Temp. [℃]	156.9	139.7
Max. Canister Surf. Temp. [℃]	219.7	186.5
Avg. Outlet Temp. [℃]	79.3	79.3
Avg. Inlet Air Vel. [m/s]	0.86	0.63
Avg. Outlet Air Vel. [m/s]	0.93	0.67
Ri No.	8.60	8.18
Eu No.	0.90	0.92

3. Conclusions

In this study, to simulate the thermal and fluid dynamics phenomena of the prototype model using a scaled-down model, a scaling analysis was performed using the similarity law to calculate the scaling ratio of the scaled-down model. Furthermore, since the dry storage module involves both heat transfer and fluid flow, thermal analysis of the scaled-down model considering the scaling ratio was conducted for thermal testing purposes. Evaluation results showed that analytically, a maximum temperature difference of up to 20 degrees Celsius was observed compared to the prototype model. Considering uncertainties associated with this result, it is deemed that using the scaled-down model is sufficiently viable for validation.

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