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Basic Considerations for Dry Storage of Spent Nuclear Fuels and Revisited CFD Thermal Analysis on the Concrete Cask

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1. Introduction

Spent nuclear fuel is being generated continually by operating nuclear reactors. Wet and dry storage are two options for preservation of spent nuclear fuel. Wet storage would place the spent nuclear fuel in a certain form of water pool and dry storage would utilize a facility or storage casks. Republic of Korea currently stores all accumulated spent fuels in on-site intermediate storage facilities. The integrity of storage facility and also of the spent nuclear fuel itself is considered very important. Storage casks can be located in a designated area on a site or in a designated storage building. A number of different designs for dry storage have been developed and used in different countries.

Dry storage system was classified into two categories by IAEA [1]. One is container including cask and silo, the other one is vault. However, there is various way of categorization for dry storage system. Dry silo and cask are usually classified separately [2], so the dry storage system can be classified into three different types. Furthermore, dry cask storage can be categorized into two types based on the type of the materials, concrete cask and metal cask.

In this paper, the design characteristics of dry storage cask are introduced and computational fluid dynamics (CFD) based thermal analysis for concrete cask is revisited.

2. Dry Storage Cask Design

Concrete cask has movable structure with one storage cavity. It can be also utilized as transportation of spent nuclear fuel. The exterior of high density concrete provides structural strength and radiological shielding. Spent fuel is loaded vertically into the cask.

The safety of a spent fuel storage facility, and the spent fuel stored within it, is ensured by: 1) containment of the radionuclides, 2) sub-criticality, 3) heat removal, 4) radiation shielding, and 5) retrievability.

Among them, heat removal inside cask is one of the most important factors affecting directly the integrity of the spent fuel in terms of degradation mechanisms, i.e. creep, SCC, hydriding, etc. In view of the decay heat generated from spent fuel, thermal analysis inside cask should be conducted appropriately for the consideration of the cask design. Natural convection through the air flow path between concrete and inner shell is induced by generating decay heat.

Safety guides for design and spent fuel storage facilities was published by IAEA [3]. The essentials of the guide are as follows.

1. Spent fuel storage facilities should be design with heat removal systems capable of cooling stored fuel when that fuel is initially loaded into the facility. The heat removal capability shall be such that the temperature of all fuel in a storage facility does not exceed the maximum temperature recommended or approved by the Regulatory Body for the type and condition of fuel to be stored. The heat removal system shall be designed to withstand all design basis accidents.
2. The heat removal system should be designed for adequate removal of heat likely to be generated by the maximum inventory of spent fuel anticipated during operation. In determining the necessary heat removal capacity, the post-irradiation cooling interval and the burnup of the fuel to be stored shall be taken into consideration. The design of heat removal systems shall include an additional margin of heat removal capability to account for processes foreseen to degrade or impair the system over time. The design of the heat removal system shall consider the maximum heat capacity of the installation.
3. In the case of certain modular facilities such as vaults, the fact that the heat produced from the decay of fuel fission products decreases with time can be taken into account. For example, in some facilities forced cooling is initially provided, after which natural cooling is adequate.
4. Redundant and/or diverse heat removal systems might be appropriate, depending on the type of storage system used, the potential for fuel overheating over an extended time and the level of conservatism necessary to provide accident mitigation
5. The design of heat removal systems for spent fuel storage facilities should include any appropriate provisions to maintain fuel temperatures at acceptable limits during the transfer of fuel.

3. Revisited CFD Thermal Analysis for Concrete Dry Cask

Recently, H. M. Kim, et al. carried out research projects on thermal analysis of concrete cask design for spent nuclear fuel [4, 5]. So we would like to revisit the result of the research, which reported temperature distribution inside cask by CFD calculation.

3.1 Cask Model for CFD Analysis

Inside a concrete cask, canister is vertically installed. The cask has circle-shaped horizontal cross section. The diameter and height of cask used in the analysis is 3.27m and 5.79m, respectively. The radial thickness of the concrete cylinder is 700mm. It includes both inner and outer surfaces of metal shell liner.

Four air inlets are placed at the lower part of the cask, and four air exits are place at the upper part. Inlet has flow area of 640mm x 150mm, and outlet has 384mm x 250mm. So the cross sectional area of the flow inlet and outlet is consistent.

Inner and the outer surfaces of the cask are covered with metal shell liners. The diameter of canister is 1.69m, and the height is 4.84m. The gap between canister and cask is 90mm.

The decay heat of one assembly of spent fuel rods was set as 800W. Total heat generated is 16.8kW with 21 assemblies of spent fuel rods in the canister.

3.2 Temperature Analysis and Result

Here is the result of thermal analysis. The ambient temperature was designated as 10℃. The intake air through the inlet had same temperature. The air in the flow path would be heated up due to the generated decay heat so natural convection would be induced. The boundary condition of heat flux was given as 556.6W/m^2 on the canister surface. The decay heat was only transferred through the surface of canister. The heat was removed by upward flowing air with convection and radiation.

The temperature distribution with the given thermal power is calculated. Heat flux was assumed to be distributed uniformly over the whole canister surface. The result of temperature distribution is shown below.

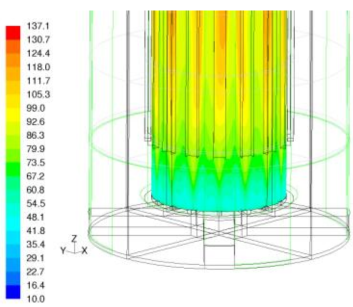

Fig. 1. Canister temperature in inlet duct.

At first, the temperature distribution on the canister surface is shown in Fig. 1 and 2. They showed the temperature distribution on the canister surface at inlet and outlet duct in detail. The highest temperature was appeared at the exit wall so the temperature at the exit duct was increased up to just before the exit temperature.

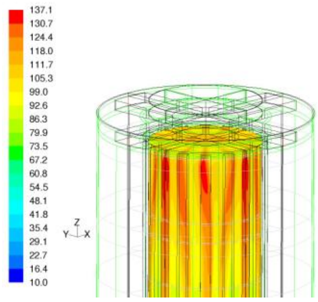

Fig. 2. Canister temperature in exit duct.

Based on the calculation of canister surface, temperature distribution inside of concrete wall calculated. The result is shown in Fig. 3 with the vertical section and along the circumferential horizontal cross section.

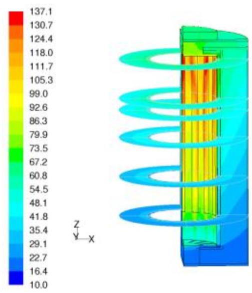

Fig. 3. Temperature distribution inside of concrete vertical section, and along the circumferential horizontal cross section

From the calculation result, the maximum concrete temperature was 86.7℃ of which was below 93℃, the design limit.

4. Conclusions

Basic principles for dry storage cask design were described. Based on that, thermal analysis of concrete dry cask was introduced from the study of H. M. Kim et al. [4, 5] From the CFD calculation, the temperature of concrete wall was maintained under the safety criteria. From this fundamental analysis, further investigations are expected. For example, thermal analysis on the metal cask, thermal analysis on horizontally laid spent nuclear fuel assemblies for transportation concerns, and investigations on better performance of natural air circulation in dry cask can be promising candidates.

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