Thermal Analysis of a Concrete Cask for the Storage of Spent PWR Fuel Assemblies

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1. Introduction

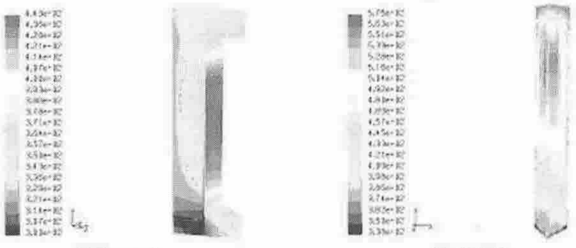
A spent fuel dry storage system is designed for the long-term storage of the spent nuclear fuel in a vertical position. The storage system consists of an overpack, sealed canister including the fuel baskets and a transfer cask. The overpack consists of the structural material, a concrete shielding, and a natural cooling system. Heat is transferred from the cask to the environment by a passive means only. Eight air inlet and outlet ducts are installed at the top and bottom for a natural cooling system. The outer diameter of the storage cask is 3,550 mm and the overall height is 5,885 mm. The gross weight of the cask is approximately 135 tons. The storage cask is designed to store 24 PWR spent fuel assemblies with a burn-up of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat load from the 24 PWR assemblies is 25.2 kW. The purpose of this paper is to perform a thermal analysis of a spent fuel storage cask in order to predict the maximum concrete and fuel cladding temperatures. Thermal analyses have been carried out for a storage cask under normal and off-normal conditions.

2. Thermal Analysis for Determination of Ventilation Ducts

Thermal analyses of the ventilation system have been carried out for the determination of the duct size and shape using the FLUENT code[1]. The thermal analysis model is only included in the air part except for the solid part of the canister and the overpack. Because most of the heat from the spent fuel is removed by a natural circulation of the cooling air. A heat flux from the spent nuclear fuel was applied to the inner surface of the air. Thermal analyses have been carried out with variations of duct sizes and duct shapes. In the result of a thermal analysis for the variation of the duct sizes, the temperatures decrease with an increasing of the duct sizes. Therefore, it is found that the thermal efficiency is enhanced in the large duct size. But the large duct size has a disadvantage from the aspect of structural and radiation shielding safeties. The duct sizes of the air inlet and outlet were selected as 290 mm x 275 mm, 425 mm x 120 mm, respectively. Thermal analyses have been carried out for an evaluation of the thermal efficiency with a variation of the ventilation duct shapes. Thermal efficiency of the ventilation duct for a straight shape is better than that of a curvilinear shape. A ventilation duct must be designed to prevent an escape to the surrounding area of a significant radiation emitting from the spent fuel. Therefore, even if it has a disadvantage in its thermal efficiency, the curvilinear passageway is selected as the shape of the air inlet duct to protect the environment from a radiation exposure through a duct opening.

3. Thermal Analysis of Storage Cask

Thermal analyses have been carried out for a dry storage cask under normal and off-normal conditions. Generally, the annual average environmental temperature is applied to the thermal analysis for a normal condition[2]. The annual average environmental temperature is about 15 ℃ in Korea, but the ambient temperature was considered as 27 ℃ in the normal condition. The off-normal severe environmental condition was selected as 40 ℃. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Four of the eight air inlet ducts are assumed to be completely blocked with an ambient temperature of 27 ℃. Solar heat flux and a maximum decay heat from the spent fuels are applied to all the analysis conditions. FLUENT analysis models were used for the three dimensional cylindrical quarter cask model. The thermal analyses were carried out in two stages to substantially increase the computational speed, as well as to reduce the requirements for the computer memory and space. In the first stage, the model consisted of the overpack, and the storage canister with a heat flux from the spent fuel. This model calculates the steady state temperature distributions of the overpack, ventilated air and canister wall. In the second stage, the canister with the fuel baskets and fuel assemblies is modeled. The canister wall temperature is applied as a boundary condition calculated from the first stage. Fig. 1 presents the temperature contours of the overpack and the canister under a normal condition. The air temperature of the upper part is considerably affected by the hot air going along the canister surface by a buoyancy force. The maximum canister wall temperature was estimated to be 170 ℃. Temperature distribution for the inside of the canister was calculated using the canister wall temperature as a boundary condition. Table 1 summarizes the calculated temperatures under a normal condition. As can be seen in this table, the maximum fuel rod temperature is lower than the allowable value for a long-term storage of the spent fuel. The fuel cladding temperature limits are typically below 380 ℃ for a 5 year cooled fuel assembly and 340 ℃ for a 10 year cooled fuel assembly. The temperature limit is about 345 ℃ for a 7 year cooled fuel assembly[3]. The maximum concrete temperature was calculated as 91 ℃, which is lower than the allowable value of 93 ℃. ACI-349[4] specifies a normal operating concrete temperature limit of 66 ℃, except for local areas which may not exceed 93 □, and a short-term or accident temperature limit of no more than 177 □. The heat discharged from the concrete cask to the environment is attained by the cooling air and heat conduction on the cask body. To determine the effects of the off-normal temperature, it is conservatively assumed that this temperature persists for a long time to allow the cask to achieve a thermal equilibrium. Table 2 shows the cask temperatures under the off-normal conditions. The temperatures for the off-normal conditions are slightly higher than those of the normal condition. The fuel rod temperature is lower than the allowable value of 570 □[5]. Also, the concrete overpack temperature is lower than the allowable limit of 177 □ under an off-normal condition.



(a) Overpack (b) Canister

Fig. 1. Temperature Contours under Normal Condition.

Table 1. Maximum Temperatures under Normal Condition

Item	Maximum temperature (□)	Allowable value (□)
Fuel rod	302	345
Canister outer surface	170	-
Overpack inner surface	91	93
Overpack outer surface	64	93
Air outlet	67	-

Table 2. Maximum Temperatures under Off-Normal Conditions

Item	Maximum temp. (□)		Allowable value (□)
	Off normal environment	Partial blockage	
Fuel rod	304	312	570
Canister outer surface	172	183	-
Overpack inner surface	97	102	177
Overpack outer surface	73	67	177
Air outlet	76	74	-

4. Conclusions

In the results of the thermal analysis for the ventilation ducts, it was found that a large size and straight shape for the ventilation ducts had an advantage from the aspect of the thermal efficiency. Optimum ventilation ducts were selected for a consideration of the radiation shielding and structural safety as well as the thermal safety. The maximum calculated temperatures of the fuel rod and concrete overpack were lower than the allowable values under the normal condition. Temperature distributions of the off-normal conditions were slightly higher than the normal condition. Therefore, the thermal integrity of the dry storage cask will be maintained under the normal and off-normal conditions.

REFERNCES

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