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Thermal Analysis of a Spent Fuel Storage Cask under Normal and Off-Normal Conditions

사용후핵연료 저장용기의 정상 및 비정상조건에 대한 열해석

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Abstract

This study presents the thermal analyses of a spent fuel dry storage cask under normal and off-normal conditions. The environmental temperature is assumed to be 15 ℃ under the normal condition. The off-normal condition has an environmental temperature of 38 ℃. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Two of the four air inlet ducts are assumed to be completely blocked. The significant thermal design feature of the storage cask is the air flow path used to remove the decay heat from the spent fuel. Natural circulation of the air inside the cask allows the concrete and fuel cladding temperatures to be maintained below the allowable values. The finite volume computational fluid dynamics code FLUENT was used for the thermal analysis. The maximum temperatures of the fuel rod and concrete overpack were lower than the allowable values under the normal and off-normal conditions.

Key words : thermal analysis, spent fuel, storage cask, heat transfer, natural convection, thermal radiation, fluid flow

Ⅰ. Introduction

The objective of a thermal evaluation is to ensure that the decay heat removal system is capable of a reliable operation so that the temperatures of the fuel assembly cladding material and storage system components remain within the allowable limits under normal, off-normal, and accident conditions. The spent fuel cladding must be protected from degradation during storage that leads to a gross fuel rupture. The zircalloy fuel cladding temperature limit at the beginning of the dry storage is typically below 380℃ for a 5-year cooled fuel assembly for normal operations and a minimum 20 years storage. The fuel temperature should also generally be maintained below 570℃ for the short-term off-normal and accident conditions. The decay heat removal system may be a passive or an active cooling system for the dry storage of the spent fuel.

A spent fuel dry storage system is designed for the long-term storage of spent nuclear fuel in a vertical position. Thermal analysis of the storage cask is based on the three heat transfer modes of conduction, convection and radiation. Heat is dissipated from the outer surface of the storage overpack to the environment by a buoyancy induced air flow and thermal radiation. Heat transfer through the cylindrical wall of the storage overpack is done by conduction. The analysis considers the passive rejection of the decay heat from the stored spent fuel assemblies to the environment under the design basis ambient conditions. Natural circulation of the air inside the storage cask allows the concrete temperature to be maintained below the allowable value and maintains the fuel cladding temperature below the limit where long-term degradation might occur.

Ⅱ. Description of Dry Storage System

A spent fuel dry storage system consists of an overpack, sealed canister including the fuel baskets and a transfer cask as shown in Fig. 1. The overpack cannot be placed in the cask pit for the loading of the spent fuel. Therefore, the canister must be carried out using the transfer cask. The canister is used in combination with the transfer cask and the storage cask components of the dry storage system.

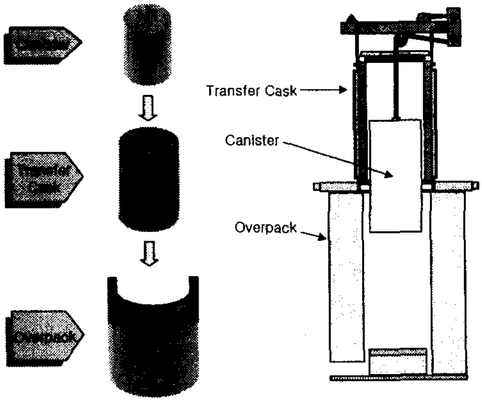


Fig.1. Spent Fuel Dry Storage System

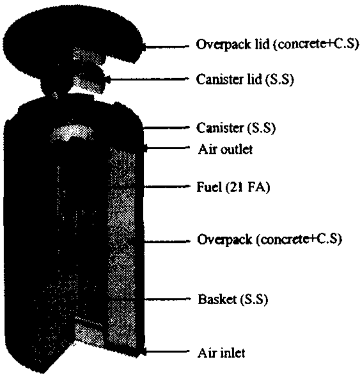


Fig.2. Overview of Concrete Cask.

Table 1. Description of the Dry Storage System

Item	Description
Storage capacity	21 PWR assemblies
Component	- Sealed canister - Concrete overpack - Transfer cask
Dimension	- Concrete overpack : O.D. 3,550 mm x 5,885 mm L - Canister : OD. 1,680 mm x 4,840 mm L
Weight	- Storage cask : 135 tons (loaded canister) - Canister : 41.4 tons (loaded fuels)
Material	- Overpack : Carbon steel, concrete - Canister : Stainless steel, boral (B4C + aluminum)
Design basis fuel	- Burn-up : 50,000 MWD/MTU - Cooling times : 7 years - Initial enrichment : 5.0 wt.% U235 - Decay heat : 22.05 kW / canister
Cooling system	- Natural cooling system - Four inlet and outlet ducts

Fig. 2 shows the overview of the storage cask. The cask consists of the structural material, concrete shielding, and a natural cooling system. Heat is transferred from the cask to the environment by a passive means only. Four air inlet and outlet ducts are installed at the top and bottom respectively. The main structure function of the overpack is provided by carbon steel, and the main shielding function is provided by concrete. The overpack is enclosed by cylindrical steel shells.

Table 1 shows the description of the dry storage 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 21 PWR spent fuel assemblies with a burnup of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat load from the 21 PWR assemblies is 22.05 kW. Four air inlet and outlet ducts are installed at the top and bottom of the cask for a natural cooling system.

Ⅲ. FLUENT Verification Analysis for Natural Convection

Kuehn and Goldstein[1] have conducted an experimental study of natural convection in a cylinder annulus. Their results serve as a good benchmark for natural convection heat transfer analysis capacity of FLUENT[2]. The purpose of this study is to compare the FLUENT analysis results with the experimental results.

Fig. 3 shows the analysis model. A heated cylinder is placed inside another cylinder, trapping air in the resulting annular cavity. As the inner cylinder is hotter than the outer, a buoyancy-induced flow results and natural convection occurs. Only half of the domain needs to be modeled from symmetry consideration. The radii of the outer and inner cylinders, respectively, are 46.3 mm and 17.8 mm. The properties of air, except density, are assumed constant and are taken to be the values at the mean temperature 350 K.

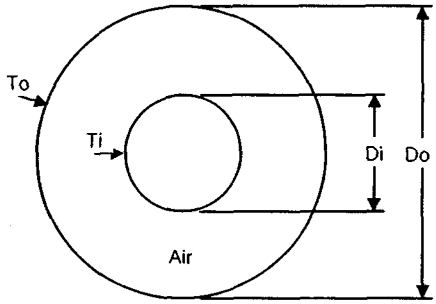


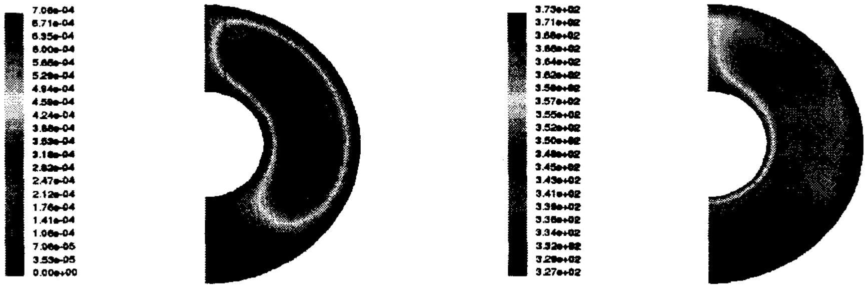
Fig. 3. Verification Model.

The Rayleigh number Ra = $g\beta\Delta TL^3/\mu\alpha$ = 4.95E4 is based on the radius of difference. The thermal coefficient of volumetric expansion β and the density ρ are evaluated at 350 K for the purpose of the Ra calculation. The body force in the negative y direction is g = 9.81 m/s^2. The inner cylinder wall is set to a temperature T_i of 373 K and the outer cylinder wall to T_o = 327 K.

Contours of stream function and temperature are shown in Fig. 4. Large velocity and temperature gradients exist in the vicinity of the hot and cold walls. The temperature and flow field results are in excellent agreement with the results of Kuehn and Goldstein. The temperature profiles along the symmetry lines are compared to the experimental data in Fig. 5. The agreement between the FLUENT predictions and the experimental data is very good. The heat flux from the inner and outer cylinder surfaces is compared with the experimental data in Fig. 6. FLUENT predictions of heat flux agree well with the benchmark experimental results. Therefore, the natural convection modeling capability of FLUENT has been validated against a benchmark result for natural convection in a horizontal cylinder annulus.

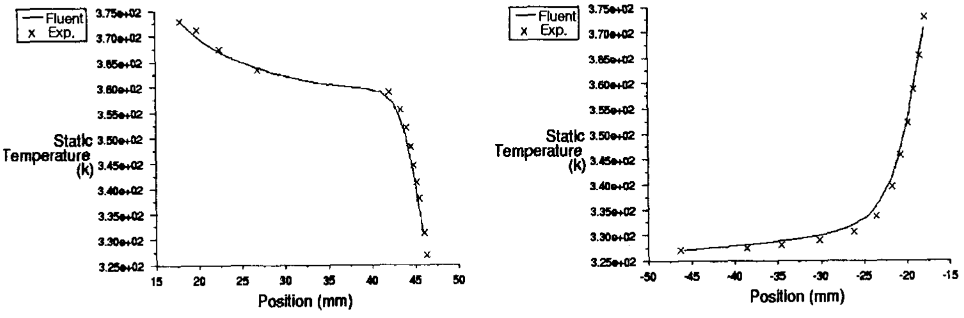
Ⅳ. Thermal Analysis Modelling

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 normal condition[3]. The ambient temperature of 15 ℃ was used to evaluate long-term fuel degradation and concrete properties and to serve as the base temperature for thermal cycle evaluations under normal condition, because the yearly average temperature is about 15℃ in Korea.



(a) Stream function (kg/s) (b) Temperature (K)

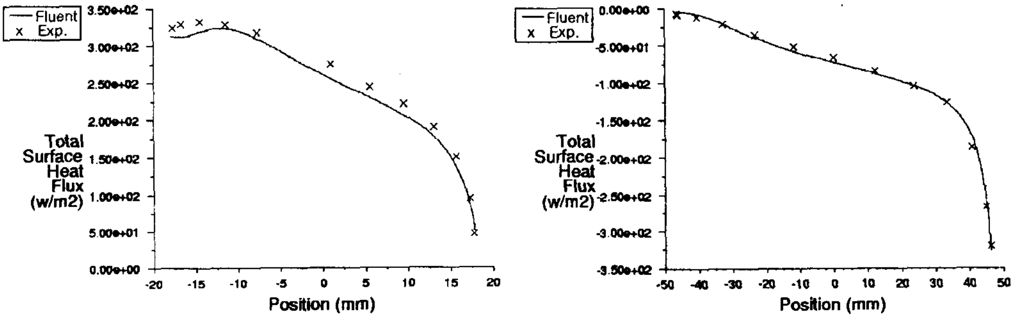
Fig. 4. Contours of Stream Function and Temperature.



(a) Top symmetry

(b) Bottom symmetry

Fig. 5. Temperature Profiles Along the Top and Bottom Symmetry Lines.



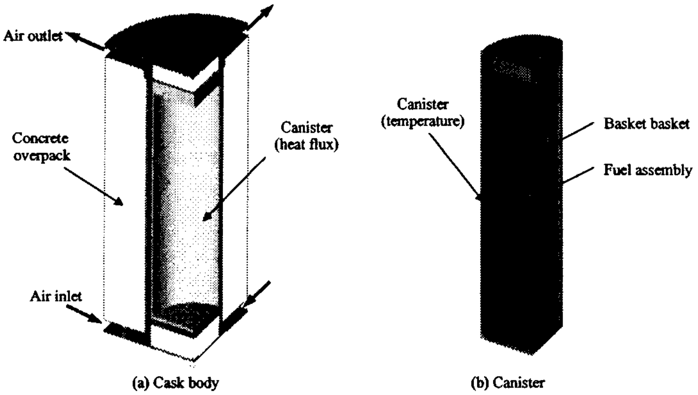
(a) Inner cylinder

(b) Outer cylinder

Fig. 6. Comparisons of Heat Flux from Inner and Outer Cylinders.

Off-normal severe environmental condition was selected as 38℃. The temperature of 38℃ is the maximum observed temperature in Korea. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Two of the four air inlet ducts are assumed to be completely blocked with an ambient temperature of 15℃. Solar insolation and maximum decay heat from the spent fuels are applied to all the analysis conditions. Decay heat from the 21 spent PWR fuel assemblies is 22.05 kW.

FLUENT analysis models were performed for the three dimensional cylindrical quarter cask model. The thermal analyses were carried out in two stages to increase the computational speed substantially, as well as reduce the requirements on computer memory and space. Fig. 7 shows the thermal analysis models for the cask body and canister. In the first stage, the model consists of the cask body, and storage canister with a heat flux from the spent fuel. The cask body model consists of 344,247 cells, 715,536 faces and 70,602 nodes. This model calculates the steady state temperature



(a) Cask body

(b) Canister

Fig. 7. Thermal Analysis Model.

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 model consists of 590,340 cells, 1,317,546 faces and 164,895 nodes. The canister wall temperature is applied as a boundary condition calculated from the first stage.

FLUENT solves conservation equations of mass, momentum and energy for flow and heat transfer calculations. The governing equations can be written as follows for rectangular coordinate.

- Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \qquad \text{---------} \quad (1)$$

Where, ρ is density, x is coordinate, and u is velocity.

- Momentum equation

$$\frac{\partial}{\partial t}(\rho u_j)+\frac{\partial}{\partial x_i}(\rho u_i u_j)=$$

$$-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i+F_j \qquad \text{--------} \quad (2)$$

Where, p is pressure, τ_{ij} is stress tensor, and ρg and F are gravitational body force and external body forces, respectively. The stress tensor is given by

$$\tau_{ij}=\mu\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_i}{\partial x_i}\right]$$

$$\text{-------------------------} \quad (3)$$

Where, μ is the molecular viscosity.

- Energy equation

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}[u_i(\rho E+p)]=$$

$$\frac{\partial}{\partial x_i}\left[k_{eff}\frac{\partial T}{\partial x_i}-\sum_j h_j J_j+u_j(\tau_{ij})_{eff}\right]$$

$$\text{-------------------------} \quad (4)$$

Where, k_{eff} is effective thermal conductivity, T is temperature, J is diffusion flux, and h is enthalpy.

Governing equation for the convective

and radiation heat transfer at the cask surface to the environment is expressed as follows.

$$q = h_{nc}A(T_s - T_a) + \sigma\varepsilon A(T_s^4 - T_a^4) \text{ ------------------------ } (5)$$

Where,

q : heat flow (W)

h : convective heat transfer coefficient (W/㎡-K)

A : cask surface area (㎡)

T_s, T_a : temperature at the cask surface and the ambient (K)

σ : Stefan-Boltzmann constant (5.669×10^{-8} W/㎡ K^4)

ε : emissivity of the surface material

Natural convection heat transfer coefficient can be derived as follows[4].

$$h_{nc} = Nu_d \frac{k}{L} \text{ ---------------- } (6)$$

Where,

$Nu_d = c(Gr\ Pr)^a$, $Gr_d = g\,\beta\,(\Delta T)d^3/\nu^2$

k : thermal conductivity (W/m-K)

a : exponent dependent on the flow regime

c : coefficient dependent on the flow regime and geometry

g : acceleration of gravity (m/s²)

L : cask length (m)

β : coefficient of the volumetric expansion (1/K)

ΔT : temperature difference between the cask surface and the ambient(K)

ν : dynamic viscosity (m²/s)

The storage cask is operated in a vertical position and the convective heat transfer coefficient is derived by the following correlations.

- Laminar range($10^4 < GrPr < 10^9$) : $Nu = 0.59\ (Gr\ Pr)^{1/4}$ ----------- (7)

- Turbulent range($Gr.Pr > 10^9$) : $Nu = 0.10\ (Gr\ Pr)^{1/3}$ ------- (8)

The cask's outer shell material is carbon steel and the surface is painted. In the thermal analysis, an emissivity of 0.85 is applied to the painted surface. The emissivities of the stainless steel and carbon steel are applied at 0.36 and 0.66.

Pressure outlet boundary conditions are used for the air inlet and outlet ducts. The gauge pressure and backflow total temperature are considered as atmospheric pressure and environmental temperatures in the pressure outlet boundary conditions.

The fuel baskets are constructed with stainless steel and boral plates, and air gaps remain between the two plates. Thermal conductivity of the composite fuel basket is based on the effective thermal conductivities for the electrical resistance analogy shown in Fig. 8. Serial and parallel conductors are calculated as follows[5].

$$\text{Serial : } \frac{1}{k_{eff}} = \frac{t_1 + t_4}{k_1 t} + \frac{2t_2}{k_2 t} + \frac{t_3}{k_3 t} \text{ --------------------------- } (9)$$

Parallel :

$$k_{eff} = \frac{k_1(t_1 + t_4) + 2k_2t_2 + k_3t_3}{t_1 + 2t_2 + t_3 + t_4} \quad \text{-----} \quad (10)$$

Where,

k_{eff} : Effective thermal conductivity

t_1, t_2, t_3, t_4 : Thicknesses of stainless steel, air, boral plate, air, and stainless steel

k_1, k_2, k_3 : Thermal conductivities of stainless steel, air gap, and boral

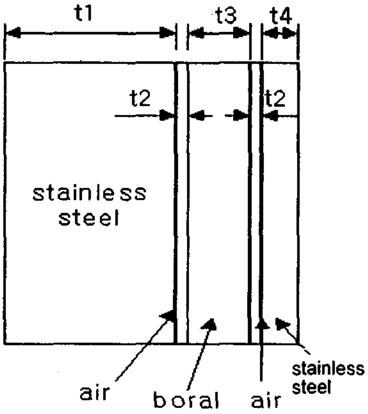


Fig. 8. Fuel Basket Model.

The porous model, which can simplify the complex configuration of a fuel assembly, has been used in the thermal analysis. Thermal conductivity, and flow resistance are modeled to approximate the fuel assembly as a porous media. Flow resistance characteristics of the fuel assemblies are used with the porous medium parameters of the permeability and the inertial resistance factor. These parameters are required to model pressure drop in porous media by FLUENT as follows.

$$\frac{\Delta P}{L} = \frac{\mu_f}{\alpha} V_s + C_I\left(\frac{1}{2}\rho_f V_s^2\right) \quad \text{---} \quad (11)$$

Where,

$\Delta P/L$: pressure drop gradient

μ_f : fluid viscosity

V_s : fluid medium superficial velocity

ρ_f : fluid density

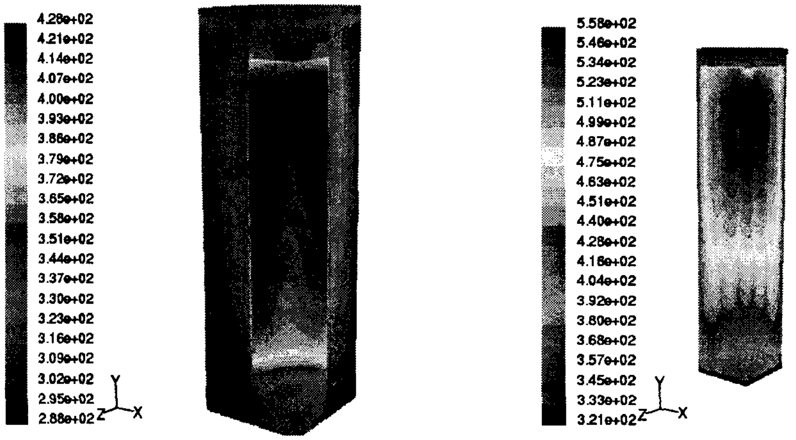
α : porous media permeability

C_I : inertial resistance factor

V. Results and Discussion

Fig. 9 presents the temperature contours of the cask body and canister under the normal condition. The air temperature of the upper part is considerably affected by the hot air going along the canister surface by buoyancy force. The maximum canister wall temperature was estimated to be 155℃. Temperature distribution for the inside of the canister was calculated using the canister wall temperature as a boundary condition.

Table 2 summarizes the calculated temperatures under the normal condition. As can be seen this table, the maximum fuel rod temperature is lower than the allowable value for the long-term storage of the spent fuel. The fuel cladding temperature limits are typically below 380℃ for a 5 years cooled fuel assembly and 340℃ for a 10 years cooled fuel assembly. The temperature limit is about 345℃ for a 7 years cooled fuel assembly[6]. Maximum concrete temperature was calculated as 72℃, which is lower than the allowable value of 93℃. ACI-349[7] specifies a normal operating concrete temperature limit



(a) Cask body

(b) Canister

Fig. 9. Temperature Contours under Normal Condition.

Table 2. Maximum Calculated Temperatures under Normal Condition

Location	Calculated temperatures (℃)	Allowable values (℃)
Fuel rod	285	345
Fuel basket	277	
Canister surface	155	
Concrete inside	72	93
Concrete outside	39	93
Air outlet	57	
Ambient	15	

Table 3. Maximum Temperatures under Off-normal Environmental Condition

Location	Calculated temperatures (℃)	
	Normal	Off-normal
Fuel rod	285	307
Fuel basket	277	299
Canister surface	155	178
Overpack inner surface	72	95
Overpack outer surface	39	62
Air outlet	57	79
Ambient	15	38

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. In the thermal analysis result, about 80 % of the heat was removed by the cooling air. It is shown that the natural convection through the air circulation is very dominant in the heat transfer of storage cask.

The off-normal environmental temperature of 38℃ is postulated as a constant temperature caused by an extreme weather condition. 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 thermal equilibrium. Table 3 shows the cask temperatures under an off-normal environmental condition. The temperatures of the off-normal condition are higher than those of the normal condition by about 23℃. The temperature difference of 23℃ is the difference of the environmental temperature. The fuel rod temperature is lower than the allowable value of 570℃[8]. Also, the concrete overpack temperature is lower than the allowable limit of 177℃ under off-normal condition.

Table 4 presents the cask temperatures for a partial blockage of the air inlet ducts. The temperatures for a partial blockage condition are slightly higher than the normal condition. It is shown that the decay heat from spent fuel can be removed through two air inlet ducts effectively. The fuel rod and concrete overpack temperatures are much lower than the allowable values under off-normal condition.

Table 4. Maximum Temperatures under Partial Blockage of Air Inlets

Location	Calculated temperatures (℃)	
	No blockage	Partial blockage
Fuel rod	285	294
Fuel basket	277	268
Canister surface	155	165
Overpack inner surface	72	82
Overpack outer surface	39	41
Air outlet	57	65
Ambient	15	15

Ⅵ. Conclusions

The ability of FLUENT to model a natural convection heat transfer has been validated using the experimental results of temperature and heat flux. 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. The fuel rod and concrete overpack temperatures were much lower than the allowable limits under the off-normal conditions. Therefore, the thermal integrity of the dry storage cask will be maintained under the normal and off-normal conditions. The thermal analysis results will be confirmed by the full scale model thermal tests next year.

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