Analysis for Thermal Test Assessment Method of Spent Fuel Concrete Cask Using a Scale Down Model

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1. Introduction

The concrete cask loaded with 21 PWR spent fuel assemblies weighs more than 100 tons [1]. Thermal test using a prototype cask is required to accurately simulate the heat transfer and flow phenomenon. However, the thermal test of a prototype cask requires much time and cost. In this study, the thermal test method using a scale down model was studied for the efficient thermal test. The purpose of this study is to derive the scale ratios to perform the thermal test using a scale down model. Scaling analyses were carried out to derive the scale ratios between the prototype cask and the scale down model. Thermal analysis and test were carried out to verify the reliability of the scale ratios and the similarity of the scale model.

2. Scaling analysis

The scale analysis was performed for three heat transfer modes.

2.1 Heat transfer mode through air flow path

Scale ratios for the condition that all decay heat is removed through the air flow path are derived as follows [2]. In this condition, the temperature of air outlet is conserved between the full scale and scale down models.

- Heat flux and heat generation rate:

$$q'' = \frac{q}{\pi D H}\ ,\ \dot{q} = \frac{q}{A_{can} H} \tag{1}$$

$$[q'']_{ratio} = [\dot{q} \times L_c]_{ratio}\ ,\ [\dot{q}]_{ratio} = \left[\frac{q'}{L_c}\right]_{ratio} \tag{2}$$

- Heat transfer rate through air outlet:

$$q = \dot{m}\, C_p (\triangle T) = \rho\, u\, A_{duct} \times C_p\, (\triangle T) \tag{3}$$

- Conservation of temperature difference:

$$[q]_{ratio} = [\dot{m}]_{ratio} \tag{4}$$

- Temperature increase at the air outlet:

$$\triangle T = \frac{q}{\dot{m}\, C_p} = \frac{\dot{q} \times A_{can} \times H}{\rho\, u\, A_{outlet} \times C_p} \tag{5}$$

$$[\dot{q}]_{ratio} = \left[\frac{u}{H}\right]_{ratio} = \left[\frac{u}{L_c}\right]_{ratio} \tag{6}$$

- Buoyancy and pressure drop from the air outlet:

$$(\triangle \rho)\, g H_p = \rho\beta\, \triangle T \times g H_p = \frac{1}{2}\rho u^2 \times f \tag{7}$$

$$u^3 = 2g\beta \frac{\dot{q}\, H}{\rho\, C_p} \frac{A_{can}}{A_{flow}} H_p \times \frac{1}{f} \tag{8}$$

- Scale ratio for velocity of air:

$$[u]_{ratio} = \frac{u_m}{u_p} = \left[\left(2g\beta \frac{\dot{q}\, H}{\rho\, C_p} \frac{A_{can}}{A_{flow}} H_p \times \frac{1}{f}\right)^{\frac{1}{3}}\right]_r \tag{9}$$

$$[u]_{ratio} = \left[\left(\frac{u}{L_c} {L_c}^2\right)^{1/3}\right]_{ratio} = \left[{L_c}^{1/2}\right]_{ratio}\ ] \tag{10}$$

- Scale ratios for heat generation rate:

$$[\dot{q}]_{ratio} = \left[\frac{u}{L_c}\right]_{ratio} = \left[\frac{{L_c}^{1/2}}{L_c}\right]_{ratio} = \left[\frac{1}{{L_c}^{1/2}}\right]_r \tag{11}$$

$$[q'\,]_{ratio} = \left[\dot{q}\, L_c\right]_{ratio} = \left[{L_c}^{1/2}\right]_{ratio} \tag{12}$$

$$[q]_{ratio} = \left[\dot{q}\, A_{can}\, H\right]_{ratio} = \left[{L_c}^{5/2}\right]_{ratio} \tag{13}$$

- Scale ratio for mass flow rate:

$$[\dot{m}]_{ratio} = [q]_{ratio} = \left[{L_c}^{5/2}\right]_{ratio} \tag{14}$$

2.2 Heat transfer mode through cask body

The scale ratios were derived under the condition that the decay heat is released to the outside through conduction of the cask body, and convection and radiation at the cask surface. In this condition, the cask surface temperature is conserved between the full scale and scale down models.

- Governing equation for cask surface:

$$q" = h(\triangle T) + \sigma\varepsilon\,(T_s^4 - {T_{amb}}^4) \tag{15}$$

- Equation of thermal conduction

$$q = kA\ \frac{\triangle T}{L_c}\ ,\ q" = k\frac{\triangle T}{L_c} \tag{16}$$

- Conservation of heat flux at cask surface

$$[q'']_{ratio} = [\triangle T]_{ratio} = 1 \tag{17}$$

- Scale ratio for temperature difference between inner and outer walls

$$[q'']_{ratio} = \left[\frac{\triangle T}{L_c}\right]_{ratio} = 1\ ,\ [\triangle T]_{ratio} = \frac{1}{2} \tag{18}$$

2.3 Heat transfer through air path and cask body

In the real cask, the decay heat from the spent fuel is removed through the air path and the cask body. In the full scale and the half scale models, 76.7 % and 63.6 % of the heat is removed through the air path. A correction factor is introduced in order to derive the scale ratios considering the heat loss form the cask body.

$$\alpha q = \dot{m}\, C_p (\triangle T) = \rho\, u\, A_{duct} \times C_p\, (\triangle T) \tag{19}$$

The correction factor(α) is expressed as the ratio of the heat transfer rate through the air path in the full scale and half scale models.

$$\alpha = \frac{q_p}{q_m} + \frac{0.767}{0.636} = 1.206 \quad (20)$$

From the equations (11) ~ (13), the scale ratios with the correction factor are calculated as follows.

$$[\dot{q}]_{ratio} = \left[\frac{1}{L_c^{1/2}}\right]_{ratio} \alpha = \sqrt{2}\alpha = 1.705 \quad (21)$$

$$[q']_{ratio} = \left[L_c^{1/2}\right]_{ratio} \alpha = \frac{1}{\sqrt{2}}\alpha = 0.853 \quad (22)$$

$$[q]_{ratio} = \left[L_c^{5/2}\right]_{ratio} \alpha = \frac{1}{\sqrt{2^5}}\alpha = 0.213 \quad (23)$$

Table 1 summarizes the scale ratios of the half scale model for three heat transfer modes.

Table 1. Scale ratios for the half scale model

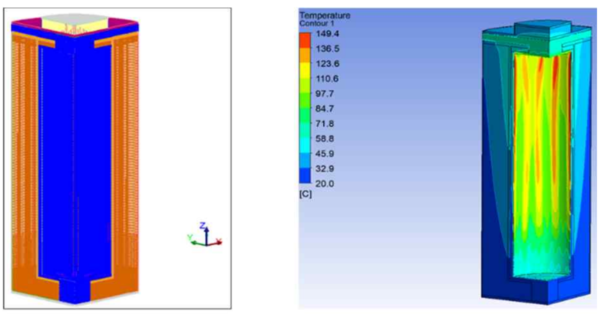
	Heat transfer modes		
	air path	Cask body	air path & cask body
$[\dot{q}]_{ratio}$	$\sqrt{2} = 1.414$	2.0	$\sqrt{2}\alpha = 1.705$
$[q']_{ratio}$	$\frac{1}{\sqrt{2}} = 0.707$	1.0	$\frac{1}{\sqrt{2}}\alpha = 0.853$
$[q]_{ratio}$	$\frac{1}{\sqrt{2^5}} = 0.177$	0.25	$\frac{1}{\sqrt{2^5}}\alpha = 0.213$
$[u]_{ratio}$	$\frac{1}{\sqrt{2}} = 0.707$	-	$\frac{1}{\sqrt{2}} = 0.707$
$[\dot{m}]_{ratio}$	$\frac{1}{\sqrt{2^5}} = 0.177$	-	$\frac{1}{\sqrt{2^5}} = 0.177$

3. Similarity analysis

The thermal analyses were performed for the prototype cask and the half scale model to verify the similarity of the scaling ratios. Steady state analysis was performed for the decay heat of 16.8 kW and ambient temperature of 20 ℃. Fig. 1 show the thermal analysis model and temperature contour for the cask.

Fig. 2 shows the radial temperature distribution for the prototype cask and the half scale model in three heat transfer modes. The temperature distributions of the prototype cask were similar to those of the scale model.

Table 2 summarizes the analysis results in the heat transfer mode of the air path and the cask body. The scale ratios of the main variables (temperature, velocity and mass flow rate) matched the results of scaling analysis in range of 3 %. Therefore, the reliability of the scale ratio and the similarity of the scale model have been proved.



(a) Thermal analysis model (b) Temperature contour

Fig. 1. Thermal analysis model and temperature contour

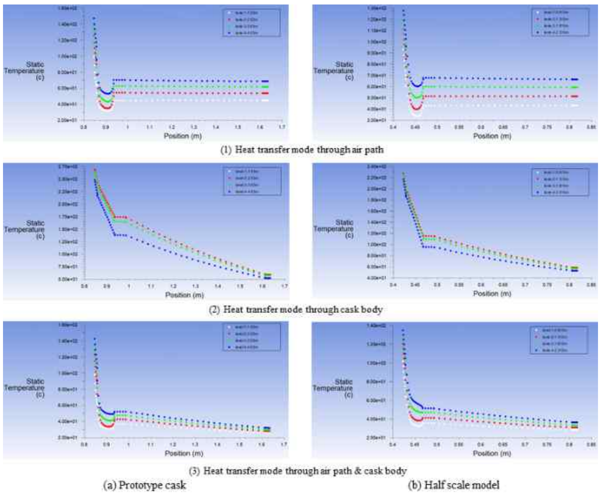


Fig. 2. Temperature distributions of prototype cask and half scale model for three heat transfer modes

Table 2. Thermal analysis results for the heat transfer mode of air path and cask body

	Prototype (q″= 1.0)	Half (q″=0.853)	Ratio
Heat source	16.8 kW	3.583 kW	0.213
Heat flux	553 W/㎡	472 W/㎡	0.853
Heat transfer rate (air path)	12.890kW (0.767)	2.278 kW (0.636)	
Air outlet temp.	63.9 ℃	62.8 ℃	0.983 (~1.0)
Air outlet vel.	0.740 m/s	0.520 m/s	0.703(0.707)
Mass flow rate (air outlet)	0.2920 kg/s	0.0509 kg/s	0.174(0.177)
Av. cask temp.	36.5	38.1	1.044
Canister temp.	96.0	93.2	0.971
Cask inside t.	44.4	43.1	0.971
Cask outside t.	29.7	32.7	1.101

4. Verification of similarity

Thermal tests were performed for the prototype cask and the half scale model to verify the thermal flow similarity of the storage cask. Fig. 3 shows the thermal test and thermal analysis results for the prototype cask under ambient temperature of 16 ℃. The thermal test results showed similar temperature profiles to the analysis results. The analysis results were slightly higher than the test results.

Fig. 4 shows the thermal test results between the prototype cask and the scale models with ambient temperature of 16 ℃. The air outlet temperature and scale ratio of velocity agree with the results of scale analysis between the prototype cask and the half scale model with the heat flux scale ratio of 0.853. Also, temperature profiles of the scale model were similar to those of the prototype cask. Therefore, the reliability of the scale ratios and the similarity of the scale models are verified.

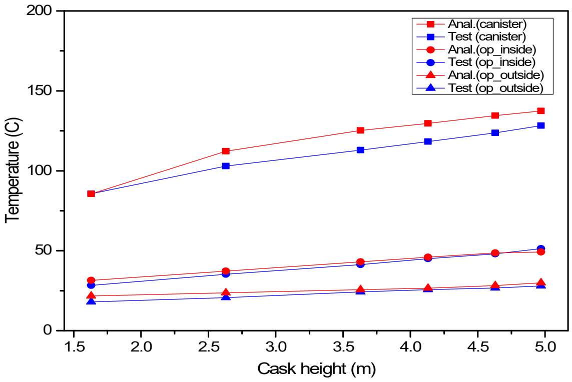


Fig.3. Temperature profiles between thermal test and analysis for prototype cask

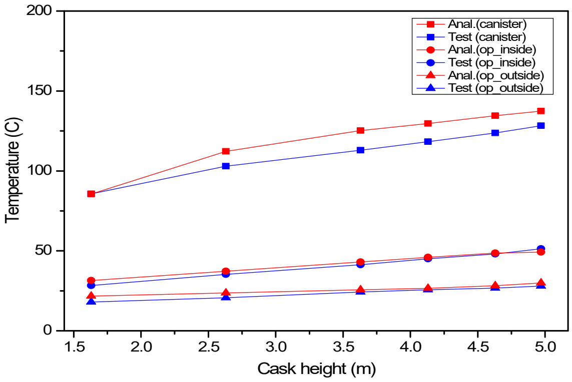


Fig.4. Thermal test results for prototype cask and scale model with various heat fluxes

5. Conclusions

The scaling analyses were performed to estimate the heat source for the thermal test using a scale down model. In the results of the thermal analysis, the scale ratios were conserved well between the prototype cask and the half scale model. The analysis results showed similar trends and patterns, and matched the test results. The thermal flow similarities have been demonstrated between the prototype cask and the scale model. Therefore, the validity of thermal test using the scale model of the storage cask has been proved. The results of this study can be used basic data for the thermal test by using the scale model of the storage cask.

REFERENCES

[1] Safety Analysis Report of Concrete Storage System, 14420-P1-N-TR-017, KORAD, 2013.
[2] H.M. Kim at al., Development of Scaling Laws of Heat Removal and CFD Assessment in Concrete Cask Air Path, Nuclear Engineering and Design, 278, 2014.