Scaling Analysis of Spent Fuel Storage Cask for Thermal Test Using a Scaled Down Model

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1. Introduction

Concrete storage cask loaded with 21 spent PWR fuel assemblies is more than 100 tons in weight. Thermal test using a full scale model requires a lot of cost and time. Therefore, a scale down model is generally used for efficient thermal test. The purpose of this study is to derive the scaling factors for simulating the thermal flow phenomenon using a scale down model, and to evaluate the similarity between the full scale and scale down models.

2. Scaling analysis of concrete storage cask

Concrete cask has four air inlet & outlet ducts, and air flow path between the cask body and canister for a natural cooling system. Decay heat generated from the spent fuel is transferred to the outside through the air circulation from the air path, conduction from the cask body, and convection & radiation from the cask surface. Scale ratios were derived based on the theoretical approach for the heat transfer through the air path and the cask body.

2.1 Heat transfer mode through air flow path

Scale ratios for the conditions that all heat is removed through the air path and the temperature at the air outlet is conserved between the full scale and scale down models are derived as follows[1].

- 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:

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

- Conservation of temperature difference:

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

- Temperature increase at the air outlet:

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

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

- Buoyancy and pressure drop from the air outlet:

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

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

$$u^3 = 2g\beta \frac{\dot{q}\, H}{\rho\, C_p} \frac{A_{can}}{A_{flow}} H_p \times \frac{1}{f} \tag{9}$$

- Scale ratio for velocity of air:

$$[u]_{ratio} = \frac{u_m}{u_p} = \left[\left(2g\beta \frac{\dot{q}\, H}{\rho\, C_p} \frac{A_{can}}{A_{flow}} H_p \times \frac{1}{f}\right)^{\frac{1}{3}}\right]_r \tag{10}$$

$$[u]_{ratio} = \left[\left(\dot{q}\, H\, H_p\right)^{1/3}\right]_r = \left[\left(\dot{q}\, L_c{}^2\right)^{1/3}\right]_{ratio} \tag{11}$$

$$[u]_{ratio} = \left[\left(\frac{u}{L_c}\, L_c{}^2\right)^{1/3}\right]_{ratio} = \left[L_c{}^{1/2}\right]_{ratio}\ ] \tag{12}$$

- Scale ratio for heat generation rate:

$$[\dot{q}]_{ratio} = \left[\frac{u}{L_c}\right]_{ratio} = \left[\frac{L_c{}^{1/2}}{L_c}\right]_{ratio} = \left[\frac{1}{L_c{}^{1/2}}\right]_r \tag{13}$$

$$[q'']_{ratio} = \left[\dot{q}\, L_c\right]_{ratio} = \left[L_c{}^{1/2}\right]_{ratio} \tag{14}$$

$$[q]_{ratio} = \left[\dot{q}\, A_{can}H\right]_{ratio} = \left[L_c{}^{5/2}\right]_{ratio} \tag{15}$$

- Scale ratio for mass flow rate:

$$[\dot{m}]_{ratio} = [q]_{ratio} = \left[L_c{}^{5/2}\right]_{ratio} \tag{16}$$

2.2 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 prototype cask, it was analyzed that about 77% of the heat was removed through the air path, and the remaining 23% was removed through the cask body. In the half scale model, about 64% of the heat was removed through the air path. Therefore, it is necessary to derive the scale ratios considering the heat loss through the cask body. A correction factor is introduced in order to derive the scale ratios considering the heat loss of the cask body.

$$\alpha q = \dot{m}\, C_p(\Delta T) = \rho\, u\, A_{duct} \times C_p\,(\Delta T) \tag{17}$$

In the equation (17), α is the correction factor of the heat source. The correction factor is expressed as the ratio of the heat transfer rate through the air path in the full scale and half scale models.

$$\alpha = \frac{q_p}{q_m} + \frac{0.767}{0.637} = 1.204 \quad (18)$$

From the equation (13) ~ (15), the scale ratios for the heat generation rates considering the heat loss from the cask body are calculated by multiplying the correction factor. Table 1 summarizes the scale ratios of the half scale model for the heat transfer modes through the air path and the cask body.

$$[\dot{q}]_{ratio} = \left[\frac{1}{L_c^{1/2}}\right]_{ratio} \alpha = \sqrt{2}\alpha = 1.702 \quad (19)$$

$$[q'']_{ratio} = \left[L_c^{1/2}\right]_{ratio} \alpha = \frac{1}{\sqrt{2}}\alpha = 0.851 \quad (20)$$

$$[q]_{ratio} = \left[L_c^{5/2}\right]_{ratio} \alpha = \frac{1}{\sqrt{2^5}}\alpha = 0.213 \quad (21)$$

Table 1. Scale ratios for a half scale model of storage cask

	Scale ratios	
	air path	air path & cask body
$[\dot{q}]_{ratio}$	$\sqrt{2} = 1.414$	$\sqrt{2}\alpha = 1.702$
$[q'']_{ratio}$	$\frac{1}{\sqrt{2}} = 0.707$	$\frac{1}{\sqrt{2}}\alpha = 0.851$
$[q]_{ratio}$	$\frac{1}{\sqrt{2^5}} = 0.177$	$\frac{1}{\sqrt{2^5}}\alpha = 0.213$
$[u]_{ratio}$	$\frac{1}{\sqrt{2}} = 0.707$	$\frac{1}{\sqrt{2}} = 0.707$
$[\dot{m}]_{ratio}$	$\frac{1}{\sqrt{2^5}} = 0.177$	$\frac{1}{\sqrt{2^5}} = 0.177$

3. Similarity analysis between full scale and scale models using a scale ratio

3.1 Heat transfer mode through air flow path

The CFD analysis was performed for a half scale model using the scale ratio obtained in the heat transfer mode through the air flow path. The air outlet temperatures were similar between the full scale and half scale models. The ratios for air velocity and mass flow rate of the air outlet in the half scale model were similar to the theoretical scale ratios. Therefore, the reliability of the scale ratios has been proven.

3.2 Heat transfer through air path and cask body

The CFD analysis was performed for the heat transfer modes through the air path and cask body. Table 2 summarizes the analysis results between the full scale and half scale models. In the full scale model, 76.7% of decay heat was removed through the air path. In the half scale model, the convection effect was reduced, and 63.7% of the decay heat was removed through the air path. The temperatures of the air outlet were calculated as 63.9°C and 62.8°C in the full scale and half scale models, respectively. The mean velocity of the air outlet is 0.520 m/s in the half scale model, which is 0.701 times compared to the full scale model.

Velocity ratio is similar to the theoretical scale ratio of 0.707. The mass flow rates at the air outlet were calculated as 0.2923 kg/s and 0.0509 kg/s in the full scale and half scale models, which is similar to the scale ratio of 0.177. Therefore, the reliability of the scale ratios has been proven. In the half scale model using the scale ratio with the correction factor, the temperature distributions were similar to those of the full scale model except for the cask surface temperature.

Table 2. CFD analysis results using scale ratios for heat transfer mode through the air path and cask body

	Full scale (q”=1.0)	Half scale (q”=0.851)	Ratio
Heat source	16.8 kW	3.574 kW	0.213
Heat flux from canister	553 W/㎡	471 W/㎡	0.851
Heat transfer rate through air path	12.886 kW (76.7%)	2.278 kW (63.7%)	.177(~.177)
Temp. of air outlet	63.87℃	62.82℃	0.984(~1.0)
ΔT(air inlet ~ outlet	43.87℃	42.82℃	0.976(~1.0)
Velocity of air outle	0.741 m/s	0.520 m/s	0.701(.707)
Mass flow rate	0.292 kg/s	0.051 kg/s	0.174(.177)
Cask’s mean temp.	36.5	38.1	1.044
Canister temp.	96.0	93.2	0.971
Cask inside temp.	44.4	43.1	0.971
Cask outside temp	29.7	32.7	1.101

4. Conclusion

Scale ratios between the full scale and scale down models were derived through the scaling analysis. As a result of the thermal analysis using the scale ratio, similar temperature distributions were obtained between the full scale and half scale models. Therefore, the similarity to the temperature was verified. Especially, it is possible to predict the overall temperature distributions of the full scale prototype cask by using the half scale model. The results of this study can be used as the basic data for the scale model thermal test of concrete cask.

REFERENCES

[1] 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).