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Scaling Methodology for a single spent fuel assembly

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1. Introduction

It is essential to find proper solutions for spent nuclear fuel management in order to secure stabilized nuclear energy supply [1]. Spent fuel discharged from operating nuclear reactors is currently stored in at-reactor storage pools. Limits for pool type storage are being reached in South Korea. As a result, South Korea needs to develop alternative storage capacity for the future [2]. Dry storage is one possible storage method. This study develops a scaling methodology for single spent fuel assembly storage.

2. Scaling Methodology

2.1 The apparatus of the single spent fuel assembly

The prototype for single spent fuel storage consists of a canister, basket and fuel assembly (Fig. 1). It is assumed that vacant space in the canister is filled with helium [3]. The model has all the characteristics of the prototype except for a half-reduced height. For scaling purpose, the canister is divided into core and downcomer region and inner and outer walls (Fig. 2). The total height of the canister is separated into top, core and bottom heights (Fig. 3).

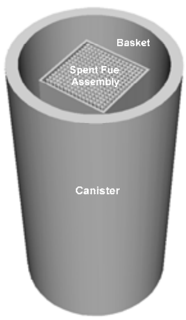

Figure 1. Schematic of the prototype single spent fuel storage unit

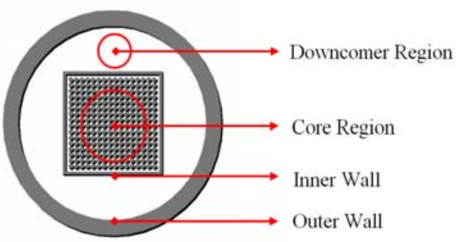

Figure 2. Top view of prototype canister

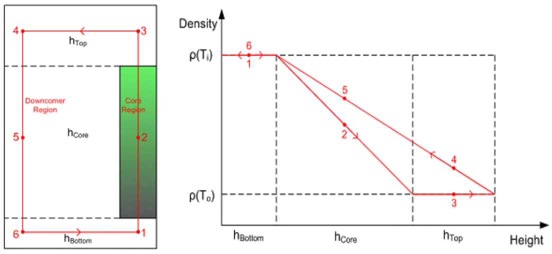

Figure 3. Relationship between canister height and density

2.2 Momentum Equation

Helium in the canister is heated by decay from spent fuel and cooled by natural circulation and radiation heat transfer. The driving force of momentum energy originates from the density difference between core and downcomer region. The driving force of natural circulation and pressure drop in the spent fuel is in equilibrium in the canister (Eq. 3).

$$\Delta P_{gravity} = \rho_o \beta g \frac{h_T}{4h_{total}}\left[3h_C + h_T\right](T_o - T_i) \quad (1)$$

$$\Delta P_{friction+form} = \frac{K}{2\bar{\rho}_c}\left(\frac{\dot{m}_{core}}{A_{core\_flow}}\right)^2 \quad (2)$$

$$\dot{m}^{*2}_{core} = [\rho_o \beta g \frac{h_T^*}{4}\left[3h_C^* + h_T^*\right]\Delta T_0 (T_o^* - T_i^*)(\frac{2\bar{\rho}_c A^2_{core\_flow}}{K\dot{m}_0^2})] \quad (3)$$

2.3 Energy Equation

Decay heat emitted by fuel rods transfers energy to the core region (Eq. 4). The energy of the core region is released to the downcomer region by radiation and convection. Transferred heat to downcomer region is removed by convection (Eq. 5).

$$\dot{m}^*_{core}\Delta T_{core}^{\ *} = [\dot{q}' N h_C - (Q_{innerwall->outerwall,radiation} + Q_{innerwall->downcomer,convection})]/Q_a \quad (4)$$

$$\dot{m}^*_{downcomer}\Delta T^*_{downcomer} = (Q_{innerwall->downcomer,convection} - Q_{downcomer->outerwall,convection})/Q_0 \quad (5)$$

The basket plate temporarily stores decay heat. Heat balance is summarized (Eq. 6).

$$(Q_{fuel->innerwall,radiation} + Q_{core->innerwall,convection}) = (Q_{innerwall->outerwall,radiation} + Q_{innerwall->downcomer,convection}) \quad (6)$$

2.4 Similarity Validation and Scaling Parameters

The conservation of similarity between prototype and model is complicated by heat transfer mechanism in the canister due to the complex geometry of spent fuel assembly and competitive heat removal by radiation, convection and conduction. The scaling parameter is determined by analytical method, and the decided parameters are implemented to CFD code for calculation to validate similarity. The ratio of temperature differences are important for basket plate, vacant space filled with helium, and between innerwall and outerwall, and should be conserved (Eq. 7-9).

$$\Delta T_w\Big|_R = \frac{\alpha_{r,m}}{\alpha_{r,p}} \times \frac{\delta_{w,m}}{\delta_{w,p}} \times \frac{k_p}{k_m} \times \frac{q''_m}{q''_p} \times \frac{N_m}{N_p} \qquad (7)$$

$$\Delta T_0\Big|_{a,R} = \frac{\alpha_{a,m}}{\alpha_{a,p}} \times \frac{\dot{q}'_m}{\dot{q}'_p} \times \frac{h_{C,m}}{h_{C,p}} \times \frac{U_{channel,p}}{U_{channel,m}} \qquad (8)$$

$$\Delta T_d = \frac{\alpha_{r,m}}{\alpha_{r,p}} \times \frac{\alpha_{rad,m}}{\alpha_{rad,p}} \times \frac{q''_m}{q''_p} \times \frac{N_m}{N_p} \times \frac{F_m}{F_p} \qquad (9)$$

For natural circulation, the ratio of helium velocity and Ra number should also be conserved (Eq. 10-11).

$$U_{channel,0}\Big|_R = \left[\frac{\left[h_T^* h_C^* [3h_C^* + h_T^*] h_{total}^2 \right]_m \alpha_{a,m} \dot{q}'_m K_p}{\left[h_T^* h_C^* [3h_C^* + h_T^*] h_{total}^2 \right]_p \alpha_{a,p} \dot{q}'_p K_m} \right]^{\frac{1}{3}} \qquad (10)$$

$$Ra\Big|_R = \frac{\alpha_{a,m}}{\alpha_{a,p}} \times \frac{\dot{q}'_m}{\dot{q}'_p} \times \frac{h_{T,m}^3}{h_{T,p}^3} \times \frac{h_{C,m}}{h_{C,p}} \times \frac{U_{channel,p}}{U_{channel,m}} \qquad (11)$$

The height of canister, the number of fuel rods and pressure loss coefficient are considered constant for the derivation. The most sensitive parameters are the ratio of heat flux, and thermal conductivity and thickness of the basket.

3. Conclusion

Scaling methodology for a single spent fuel assembly has been developed. The scaling parameters to implement in CFD code have been decided on the basis of an analytical method. The parameters to be controlled are considered as the ratio of heat flux, and thermal conductivity and thickness of the basket.

REFERENCES

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