Numerical assessment of the RVCS model developed by the scaling analysis using MARS-KS code

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1. Introduction

The Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) is one of the Generation IV Reactors (Gen-IV), currently being developed by Korea Atomic Energy Research Institute (KAERI). PGSFR is a pool type reactor consisting of Reactor vessel (RV) and Containment vessel (CV). Decay heat removal system (DHRS) consists of two passive decay heat removal systems (PDHRS) and two active decay heat removal systems (ADHRS) [1]. There is also a Reactor vault cooling system (RVCS), which is designed to prevent the increasing temperature of the concrete structure and Vessels (Fig. 1.) [2, 3].

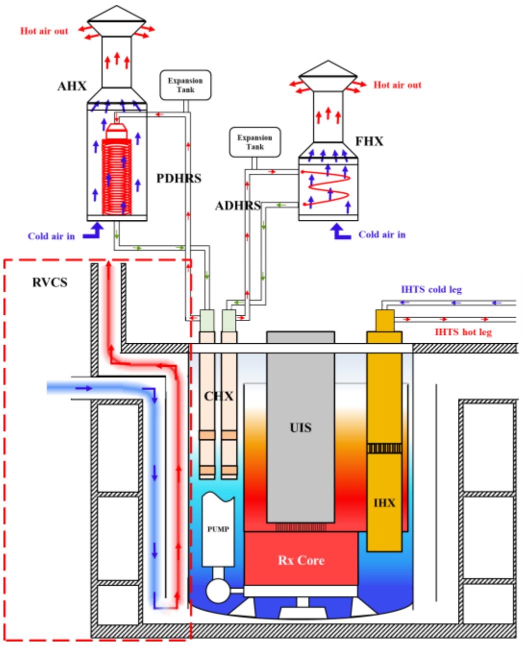

Fig. 1. PGSFR Decay Heat Removal Systems

2. Development of scale-down model of RVCS

2.1. Non- dimension Governing Equations [4]

The inner SP heated by the radiative heat must be insulated so as not to interfere with the downflow between the CW and the outer SP by blocking the heat transferred to the CW by the insulator (outer SP). Therefore, the heat transferred from the outer surface to the CW was not considered. The heat transferred from the RV to the CV was assumed to be a boundary condition and only the heat transfer between the CV and the inner SP was considered. In addition, the bottom of CV hemispheric geometry was not considered and the RVCS was regarded as a simplified U shape.

The transferred heat from CV (Q_{CV}) separated the convective heat to the air ($Q_{Conv,CV}$) and the radiative heat to Inner SP ($Q_{Rad,CV}$). And then, the radiative heat is converted to the convective heat from SP to the air by the assumption that Outer SP is well insulated on steady state condition. The energy balance equation is set as following

$$Q_{CV} = Q_{Conv,CV} + Q_{Rad,CV} = Q_{Conv,CV} + Q_{Conv,SP} \tag{1}$$

One dimensional conservation equations take the following form from Ishii & Kataoka [5]

Non-dimensional Continuity equation

$$U_i = U_r / A_i \tag{1}$$

Non-dimensional Integral momentum equation

$$\frac{dU_r}{d\tau}\left(\sum_i \frac{L_i}{A_i}\right) = \left(\frac{g\beta\Delta T_0 l_0}{u_0^{\,2}}\right)(\theta_h - \theta_c)L_h - \frac{(U_r)^2}{2}\sum_i\left(\frac{F_i}{A_i^2}\right)^2 \tag{2}$$

Non-dimensional Energy equation for liquid

$$\left\{\frac{\partial\theta_f}{\partial\tau} + \frac{U_r}{A_i}\frac{\partial\theta_f}{\partial Z}\right\} = \left\{\frac{4h_{CV}l_0 d_{CV}}{\rho C_p u_0\left(d_{SP}^{\,2} - d_{CV}^{\,2}\right)}\right\}(\theta_{w,CV} - \theta_f) + \left\{\frac{4h_{SP}l_0 d_{SP}}{\rho C_p u_0\left(d_{SP}^{\,2} - d_{CV}^{\,2}\right)}\right\}(\theta_{w,SP} - \theta_f) \tag{3}$$

Modified Richardson number is proposed to represent the ratio of buoyancy force to inertia force based on changing the air temperature difference at the inlet and outlet. Because the objective of this research is prediction of the heat removal rate determined by flow rate and temperature difference between inlet and outlet of the air. Stanton number also change due to different geometry of RVCS. But the physical meaning is maintained.

Modified Richardson number (Ri*#)

$$Ri^* = \left(\frac{g\beta\Delta T_0 l_0}{u_0^2}\right) = \left(\frac{Buoyancy}{Inertia}\right) \quad (4)$$

Modified Stanton number (St#)

$$St = \left(\frac{4hd_0 l_0}{\left(d_{CV}^{\ 2} - d_{SP}^{\ 2}\right)\rho C_p u_0}\right) = \left(\frac{Wall\ convection}{Axial\ convection}\right) \quad (5)$$

Friction number

$$\sum_i \left(\frac{F_i}{A_i^2}\right) = \left(\frac{fl_o}{d_o} + K\right) = \left(\frac{Friction}{Inertia}\right) \quad (6)$$

2.2 Scaling analysis [4]

Scaling analysis is performed to find the ratios of the variables between the prototype and model. The ratio between the model and prototype is denoted by R as following [5].

$$\Pi_R = \frac{\Pi_{model}}{\Pi_{prototype}} \quad (7)$$

Considering the space limitations that can be used for experiments while minimizing distortion, the model is selected to 3m height of the model and the heat flux ratio and the flow velocity ratio are also determined that 1.22 and 0.67 relatively (Table 1).

l_R	l [m]	d_R	d [m]	u_R	q''_R	ΔT_R	$Ri\#_R$
0.10	0.67	0.56	0.17	0.32	1.78	1	1
0.30	2.01	0.74	0.22	0.55	1.35	1	1
0.45	3.00	0.82	0.25	0.67	1.22	1	1
0.60	4.02	0.88	0.26	0.77	1.14	1	1
0.75	5.03	0.93	0.28	0.87	1.07	1	1
0.90	6.03	0.97	0.29	0.95	1.03	1	1
1.00	6.70	1.00	0.30	1.00	1.00	1	1

Table. 1 Different Models based on the scaling law

3. MARS-KS code simulation

To evaluate the validity of the developed model, MARS-KS Code simulation is performed on the constant heat flux condition in the prototype and scale-down model. The MARS (Multi-dimensional analysis of reactor safety) code is the thermal-hydraulic system code for analysis of reactor transients. And, the heat removal performance also was compared with prototype and model. The air path modeled as a riser pipe (201) where the air is heated by convection in the CV and the SP and a down comer pipe (100) where the air flows, a horizontal pipe (101) connecting a down comer and a riser, a discharge pipe (202) were modeled in MARS-KS. In case of discharge pipe, form loss coefficient can be set individually assuming that the damper is installed to satisfy Friction number similitude. To suppress the flow caused by the pressure head effect, the height of discharge and down comer was set to be same. Also, additional heat structure was set in the outlet of the horizontal pipe and the inlet of the discharge, and the radiation heat flux was calculated assuming that it was an enclosure (Fig. 2).

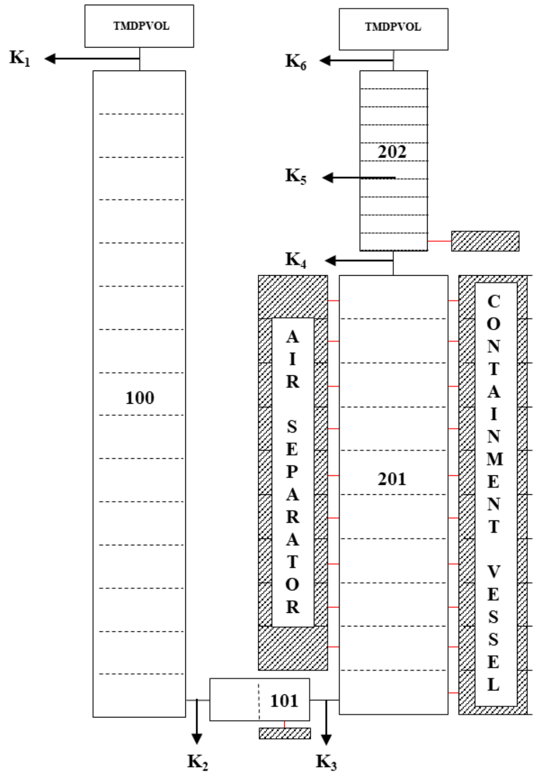

Fig. 2. RVCS model in MARS-KS

Assuming that the metal plate constituting the wall is polished well, the emissivity of the CV and SP wall are set by 1.5 and 2, respectively [6]. The form loss coefficient for the shape was determined by referring to the ASHRAE Handbook [7].

3. Conclusions

To assess the validity of the scaled model based on scaling analysis, it was compared the prescribed average velocity ratio (u_R=0.67) and temperature difference ratio between outlet and inlet ($\triangle T_R$=1) for the prototype and the scaled model with respect to the different form loss coefficient among scale down cases.

In Fig. 3, comparing the air temperature difference with the prototype and the scaled model, in the case of K=2.5, the temperature difference ratio related with the buoyancy effect is 1.004, which is most analogous to the prescribed temperature difference ratio ($\triangle T_R$=1). In terms of the average velocity ratio related with inertia effect, it was confirmed that the flow velocity ratio was 0.669 in the case of K=2.0, which is most analogous to the prescribed average velocity ratio (u_R=0.67)

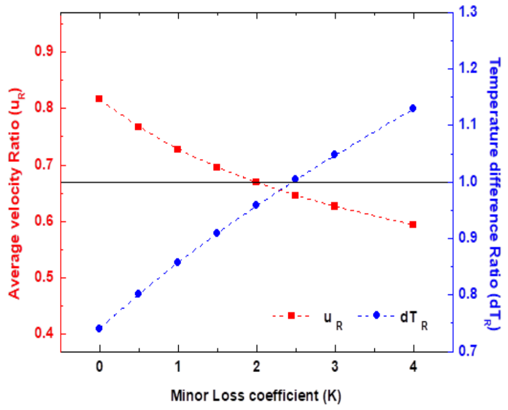

Fig. 3. Comparative Results of Average Velocity Ratio and Temperature Difference Ratio

The wall temperature of the CV and SP and the air temperature distribution are compared according to the height of prototype and scaled model (K = 2.0). The air temperature and flow velocity can be predicted appropriately, but the temperatures of the CV and SP are slightly different. In fact, the scaled model requires higher heat fluxes condition (q''_R = 1.22) and slower flow velocity (u_R = 0.67), so the wall temperature of the scale model is higher (Fig. 3).

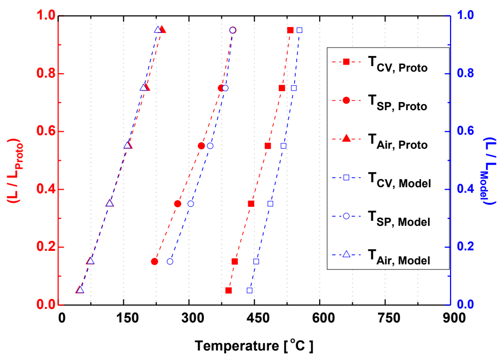

Fig. 3 Axial Temperature Distributions

To check the flow regime in the natural convection, the Rayleigh number (Ra_L) of the prototype and scaled model were compared. It has been confirmed that both Prototype and scaled model exceeds critical Rayleigh number (~ 10^9), which is commonly known as the judgement criterion of turbulent flow on natural convection in vertical plate. Reynolds number (Re_D #) of the scaled model was slightly smaller than 2900, which is known as the fully turbulent region in pipe flow, but not significantly changed. Therefore, the validity of the model developed through the scale analysis has been verified.

After all, a comprehensive assessment of the above results is that the K = 2.0 model is best suited as a scaled model. Also, these results indicate that the proposed scaling analysis method predicts the RVCS cooling performance adequately and estimates the wall temperature slightly higher. This conservative evaluation ensures reliability of NPPs.

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