Scaling analysis for scale down in RVCS air natural circulation experimental facility

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1. Introduction

Sodium-cooled Fast Reactor (SFR), one of the Generation-IV (Gen-IV) nuclear reactors, has many advantages such as high efficiency, no pressurization etcs. Argonne National Laboratory (ANL), one of the frontier research institutes, suggested a design concept of passive reactor cooling system that remove heat utilize decay heat by natural convection; Reactor Vessel Auxiliary Cooling System (RVACS). [1]. Similarly, a Reactor Vault Cooling System (RVCS) was adopted for the safety feature of Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR), which was designed by Korea Atomic Energy Research Institute (KAERI) as shown in Fig. 1. The RVCS is a cooling system to protect the vessel from exceeding limited temperature range. It should satisfy ASME level D to reactor and ASME section III to concreate of structure [2]. Considering heat transfer phenomena in RVCS, this system consists of Reactor Vessel (RV), Liquid sodium in RV, Argon gas in the Containment Vessel (CV) and concreate structure that functions as an air natural circulation path (Fig. 2.). In nuclear industry, however, there are many limitations for developing an experimental facility in real-scale reactor, or material similarity. Eventually, many experiments are tended to be substituted as some experimental simulations based on different scale and materials. One of the representative methods is scaling analysis [3, 4], which validates the experimental facilities in reduced scale. For example, the scaling analysis was applied in PMR200 - Reactor Cavity Cooling System (RCCS) experimental facility to reduce the scale [5]. And, scaling analysis was also applied in experimental facility of Decay Heat Removal System (DHRS) in PGSFR to replace sodium coolant with another liquid metal [6]. In this study, the scaling analysis was applied to design the air natural circulation experimental facility and develop the scale down model, based on a prediction of the thermal and fluid behavior in RVCS prototype.

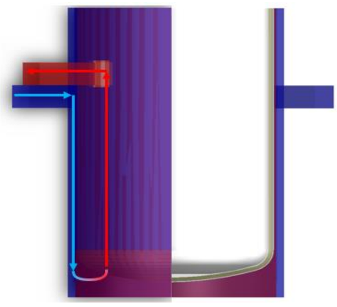

Fig 1. Schematics of RVCS and air path

2. Non- depersonalization of Governing Equation

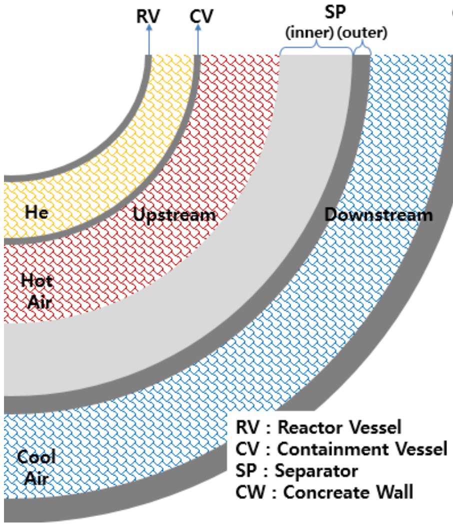

Fig 2 RVCS - plan view

Complex heat transfer mechanisms are coupled in RVCS. In the RVCS, decay heat generated in core is transported from reactor vessel (RV) to containment vessel (CV) by natural convection and radiation. And then, air between CV wall and separator (SP) is heated by natural convection and the inner wall of SP is heated by radiation. SP consists of two different materials. To not obstruct natural circulation as the buoyancy effect generated by air heating in downstream path, outer SP consists of thermal insulator.

In this study, it is only considered to heat transported from CV to SP and air without considering the heat transported from RV to CV. We also assume that the geometry of air path is simplified U-shaped path excepting for tori-spherical bottom head. One dimensional conservation equations (Eq. (1) - (3)) take the following form [4].

Continuity equation

$$u_i = \frac{a_0}{a_i} u_r \tag{1}$$

Integral momentum equation

$$\rho \frac{du_r}{dt}\left(\sum_i \frac{a_0}{a_i} l_i\right) = \rho g \beta \Delta T l_h - \frac{\rho (u_r)^2}{2} \sum_i \left(\frac{fl}{d} + K\right)\left(\frac{a_0}{a_i}\right)^2 \tag{2}$$

Energy equation for solid

$$\rho_s C_{ps}\frac{\partial T_s}{\partial t} + k_s\nabla^2 T_s - \dot{q}_s = 0 \tag{3}$$

But energy equation for liquid (Eq. (4)) and boundary conditions (Eq. (5) - (6)) could not take same form. It is different in heat transfer mechanism of RVCS, which is the air is heated not only by CV wall but by SP wall. The surface between CV and air simultaneously transfer heat by convection to adjoining gas and by radiation to SP wall. When the outer SP assumed adiabatic, the heat transferred by radiation on SP surface transfer by convection to adjoining gas (Fig. 3.).

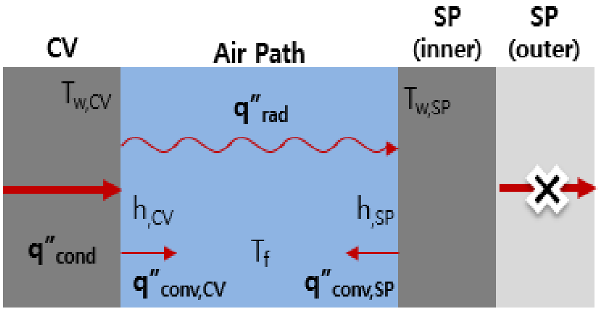

Fig 3. Heat transfer mechanism in RVCS air path

Following the energy equation for liquid (Eq. (4)), the right-hand side two terms are modified as geometric difference. The second term of them is added to consider transferred radiative heat from CV to SP.

Energy equation for fluid

$$\rho C_p\left\{\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial z}\right\} = \frac{(4h_{CV}d_{CV})}{(d_{SP}^2-d_{CV}^2)}(T_{CV}-T_f) + \frac{(4h_{SP}d_{SP})}{(d_{SP}^2-d_{CV}^2)}(T_{SP}-T_f) \tag{4}$$

Boundary condition between CV and air

$$-k_s\frac{\partial T_s}{\partial y} = h_{CV}\left(T_{w,CV}-T_f\right)+q''_{rad} \tag{5}$$

Boundary condition between SP and Air

$$q''_{rad} = \frac{d_{SP}}{d_{CV}}h_{SP}\left(T_{w,SP}-T_f\right) \tag{6}$$

In the above equations, q" is heat flux and h is convective heat transfer coefficient. Subscripts CV, SP, w, f, cond, conv and rad denote each other the Containment Vessel, Separator, wall, fluid, conduction, convection and radiation. The above set of equations can be non-dimensionalized by the following form [4].

Non-dimensional Continuity equation

$$U_i = U_r/A_i \tag{7}$$

Non-dimensional Integral momentum equation

$$\frac{dU_r}{d\tau}\left(\sum_i\frac{L_i}{A_i}\right) = \left(\frac{g\beta\Delta T_0 l_0}{u_0^2}\right)(\theta_h-\theta_c)L_h - \frac{(U_r)^2}{2}\sum_i\left(\frac{F_i}{A_i^2}\right)^2 \tag{8}$$

Non-dimensional Energy equation for solid

$$\frac{\partial\theta_s}{\partial\tau} + \left(\frac{\alpha_s l_0}{\delta^2 u_0}\right)\nabla^{*2}\theta_s - \left(\frac{\dot{q}_s l_0}{\rho_s C_{ps} u_0\Delta T_0}\right) = 0 \tag{9}$$

Non-dimensional Energy equation for liquid

$$\left\{\frac{\partial\theta_f}{\partial\tau}+\frac{U_r}{A_i}\frac{\partial\theta_f}{\partial Z}\right\} = \left\{\frac{4h_{CV}l_0 d_{CV}}{\rho C_p u_0\left(d_{SP}^2-d_{CV}^2\right)}\right\}\left(\theta_{w,CV}-\theta_f\right) + \left\{\frac{4h_{SP}l_0 d_{SP}}{\rho C_p u_0\left(d_{SP}^2-d_{CV}^2\right)}\right\}\left(\theta_{w,SP}-\theta_f\right) \tag{10}$$

The non-dimensional groups extract in the above equations.

Richardson number

$$Ri = \left(\frac{g\beta\Delta T_0 l_0}{u_0^2}\right) \sim \left(\frac{Buoyancy}{Inertia}\right) \tag{11}$$

Modified Stanton number

$$St = \left(\frac{4hd_0 l_0}{\left(d_{CV}^2-d_{SP}^2\right)\rho C_p u_0}\right) \sim \left(\frac{Wall\ convection}{Axial\ convection}\right) \tag{12}$$

Friction number

$$\sum_i\left(\frac{F_i}{A_i^2}\right) = \left(\frac{fl_o}{d_o}+K\right) \sim \left(\frac{Friction}{Inertia}\right) \tag{13}$$

3. Scaling analysis

The driving force of air flow in RVCS is buoyancy induced by air temperature difference. So, we set the similarity in temperature difference between air inlet and outlet temperatures (Eq. (14)). It involves similarity of same material property associated with temperature variable (Eq. (15)).

$$\Delta T_R = 1 \tag{14}$$

$$\rho_R = \left(C_p\right)_R = \beta_R = 1 \tag{15}$$

This study is focus on predicting the natural circulation velocity of the air. A Similarity in Richardson number (Eq. (16)) is easily determined velocity ratio owing to similarity in temperature difference.

$$Ri_R = \left(\frac{l_0}{u_0^2}\right) = 1 \tag{16}$$

$$l_0 = u_0^2 \tag{17}$$

To preserve similarity in Richardson number, it must also satisfy the Friction number similarity (Eq. (18)).

$$\sum\left(\frac{F}{A^2}\right)_R = 1 \tag{18}$$

Because The friction number is only geometrical variable, it is easily to satisfy using orifices or damper in experiment.

Energy balance equation is always satisfied as unchangeable Law (Eq. (19)).

$$Q_{system} = \rho A u C_p \Delta T_f = q_w'' A_w \tag{19}$$

We consider similarity of energy balance, which results in a requirement of the following equation.

$$q''_{wR} = \frac{u_{0R} d_R}{l_{0R}} = \frac{d_R}{l_{0R}^{0.5}} \tag{20}$$

It is impossible that the Richardson number and Stanton number similarities are preserved simultaneously. The natural convection heat transfer correlation (Eq. (21)), which is reflected in the scale analysis [7].

$$Nu_x = \frac{hx}{k} = 0.204\left[Ra_x^* \frac{d}{l}\right]^{0.5} \tag{21}$$

$$St_R = \left(\frac{h l_0}{u_0 d_0}\right)_R = \left(\frac{h l_0^{0.5}}{d_0}\right)_R = \left(\frac{d_R}{l_{0R}^{1/4}}\right) \tag{22}$$

However, the heat transfer phenomena could not be appeared similarly in the two different scale systems, rather it can be used to decide relation between length and velocity ratios left in Eq. (17). The distortion caused by applying correlation will be checked by comparing heat transfer coefficient obtained from experimental data.

4. Conclusion

In this study, scaling analysis is applying to reduce air natural circulation facility, to predict the flow rate of natural circulation in the real scale RVCS. The distortion of heat transfer coefficient applying scaling analysis should be checked by comparing heat transfer coefficient obtained from experimental data. Based on these studies, we will carry out a comparative CFD analysis to validate.

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