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The Effect of Duct Level on the Performance of Reactor Vault Cooling System in the PGSFR

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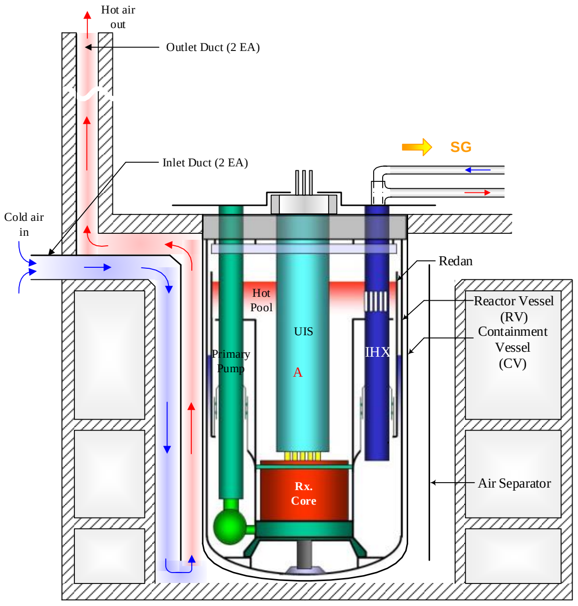
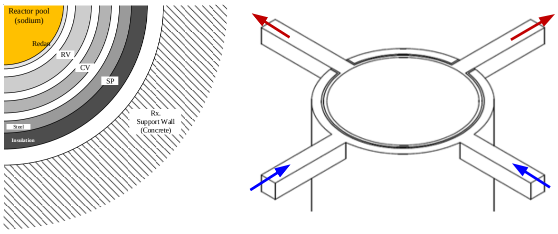
1. Introduction

Development of the prototype gen-Ⅵ sodium-cooled fast reactor (PGSFR) has been ongoing in Korea Atomic Energy Research Institute (KAERI). A reactor vault cooling system (RVCS), one of passive decay heat removal systems (PDHRS), passively removes core decay heat by chimney effect when severe accidents occur. The schematic view is shown in Fig. 1. The air cooling path is located around containment vessel (CV). An air separator which divides the downstream air and the upstream air is installed between CV and the concrete wall. At the downstream air path, the air is introduced by chimney effect. At the upstream air path, the heat is removed from CV to air and the path is connected to chimneys at the outlet.

RVCS should satisfy ASME level D to sufficiently cool the reactor and ASME section Ⅲ to assure the structural reliability of concrete at the air path. To design the RVCS, key design parameters such as stack height, gap size between the concrete wall and the air separator, gap size between the air separator and the CV, thickness and layer composition of the air separator have to be determined. A duct level is one of these design parameters. It denotes the height of the upstream air path and related to the heat transfer length from CV to air. The duct level should be optimized with considering structural reliability and heat removal performance. Thus, in this paper, the heat removal performance of RVCS is evaluated depends on the duct level using 1D system design code, that is developed by KAERI autonomously[1], and commercial CFD program for optimum design of RVCS.



(a) Front view



(b) Plan view (c) Direction of inlet and outlet

Fig. 1. Schematic view of RVCS

2. 1D system code analysis

2.1 Method

To design and analyze the RVCS thermal hydraulic characteristics, a 1D system code (PARS2-LMR) has been developed which modeled convection, conduction, and radiation heat transfers through the heat transfer path of the RVCS, namely from reactor core to air. It solves momentum and energy equations and finds induced air flow rates and system temperature. An equivalent thermal circuit of the RVCS is described in Fig. 2 and applied equations are as follows.

Momentum equation:

$$\frac{\partial \dot{m}}{\partial t}\sum\frac{\Delta S_{\mathrm{i}}}{A_{\mathrm{i}}} = \oint \rho g\cdot ds - \frac{\dot{m}^2}{2}\sum\frac{1}{\rho_i A_{\mathrm{i}}^2}\left(K_{\mathrm{i}} + f_{\mathrm{i}}\cdot\frac{\Delta S_{\mathrm{i}}}{d_{\mathrm{i}}}\right)$$

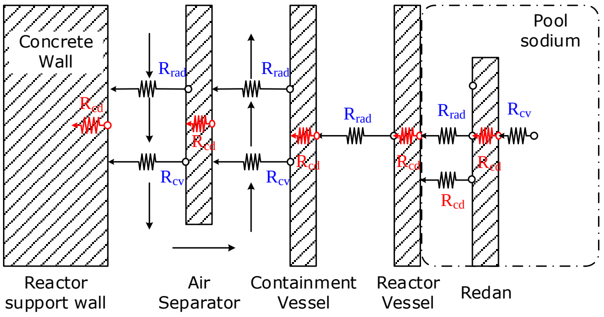


Fig. 2. Equivalent thermal circuit of RVCS

Energy equation for air:

$$\frac{\partial}{\partial t}\left(A_{\mathrm{n}}\Delta x\rho C_{\mathrm{P}}T\right)_{\mathrm{i}}=\dot{m}\left(\overline{C_{\mathrm{P,in}}}T_{\mathrm{in}}-\overline{C_{\mathrm{P,out}}}T_{\mathrm{out}}\right)+Q_{\mathrm{CV}}$$

Energy equation for sodium:

$$\frac{\partial}{\partial t}\left(A_{\mathrm{n}}\Delta x\rho C_{\mathrm{P}}T\right)_{\mathrm{i}}$$
$$=\dot{m}\overline{C_{\mathrm{P,in}}}(T_{\mathrm{in}}-T_{\mathrm{out}})+(Q_{\mathrm{Redan}}-Q_{\mathrm{RV}})+Q_{\mathrm{cond,st}}+Q_{\mathrm{decay\,heat}}$$

In the momentum equation, friction and form losses are calculated by utilizing empirical correlations. When the air flow resistance is balanced with the naturally developing head, the mass flow rate of air is obtained. The heat from the core is transferred to the introduced air and finally removed. Dittus-Boelter equation and Skupinshi's equation are used to calculate convection heat transfer coefficient for air and sodium, respectively, as follows.

Dittus-Boelter equation : $Nu = 0.023\cdot \mathrm{Re}^{0.8}\cdot \mathrm{Pr}^{0.4}$

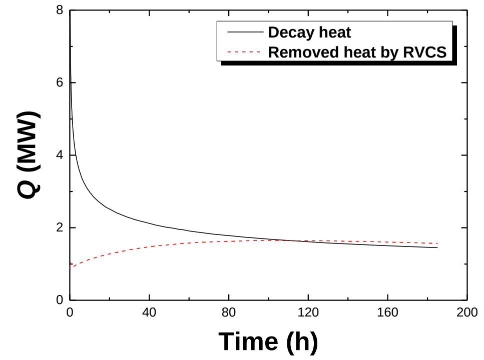
Skupinshi equation : $Nu = 4.82 + 0.0185\cdot Pe^{0.827}$

2.2 Result

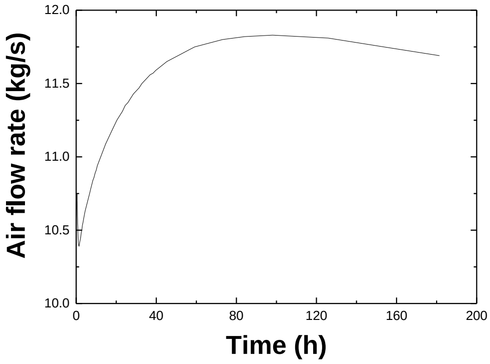
The analyzed results using the PARS2-LMR code are as follows. Fig. 3 shows the general trends of PGSFR thermal characteristics with RVCS cooling after severe accidents occurrence. At an early stage, the temperature of reactor vessel (RV) increases because the core decay heat is larger than the heat removal rate of the RVCS as shown in the Fig. 3(a). As time passes, the RVCS heat removal rate gets larger as the air flow rate increases as shown in Fig. 3(b). When the RVCS heat removal rate exceeds the core decay heat rate, RV temperature starts to decrease. Thus thermal hydraulic design of the RVCS should be conducted based on the maximum RV temperature that is obtained when the core decay heat rate is overtaken.

The Fig. 4 and Fig. 5 shows the heat removal rates of the RVCS and the maximum temperature of RV with variation of duct level from 9m to 13.7m, the maximum level of PGSFR. Here, the number of inlet and outlet ducts are two for each and the hydraulic diameter and height of duct are 1.2m and 30m, respectively. As shown in the figures, the heat removal rate increases and the maximum temperature of RV decreases as the duct level increases. Furthermore, the maximum temperature of RV decreases with decreases of upstream gap size as previously reported by Eoh et al. and Kim et al.[1, 2, 3]. From the 1D code analysis, the design value is obtained in the ranges of RVCS geometries in this paper. The duct level should be larger than 10m when the upstream flow path gap size is 0.1m. However, when the gap size is 0.2m, the duct level should be larger than 12m.

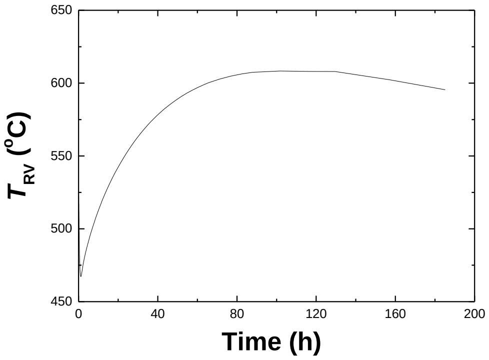
Fig. 6 shows the exiting air temperature with variation of duct level over the whole range of tested conditions, it is larger than 150 degree and even larger than 175 degree for the case of 0.1m upstream gap size. This condition is not preferable for the reliability of concrete. Thus, it is deducted that an additional design to avoid direct contact of upstream air to concrete should be considered.



(a) Decay heat and removed heat



(b) Air flow rate



(c) RV temperature

Fig. 3. General characteristics of RVCS after severe accident

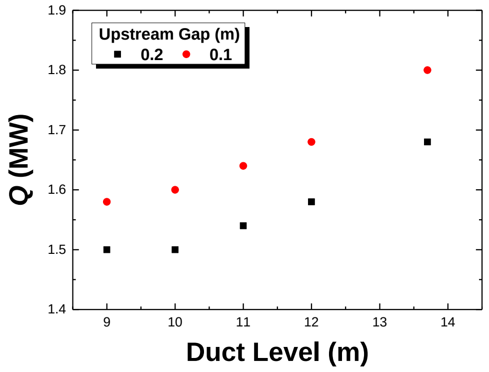


Fig. 4. Heat removal rate with duct level variation

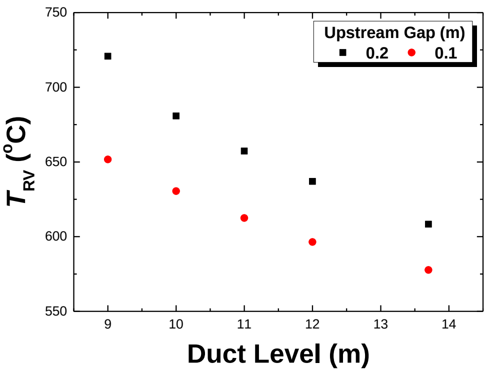


Fig. 5. RV temperature with duct level variation

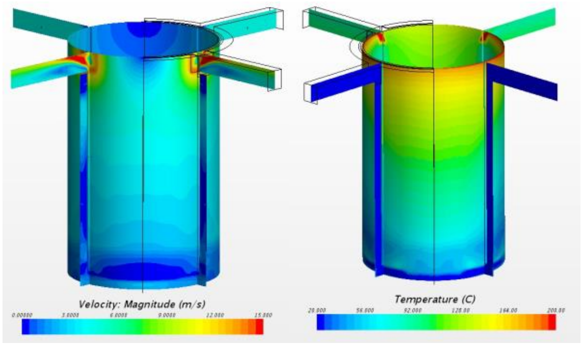


Fig. 7. Velocity (left) and Temperature (right) distribution when *L* = 13.7m.

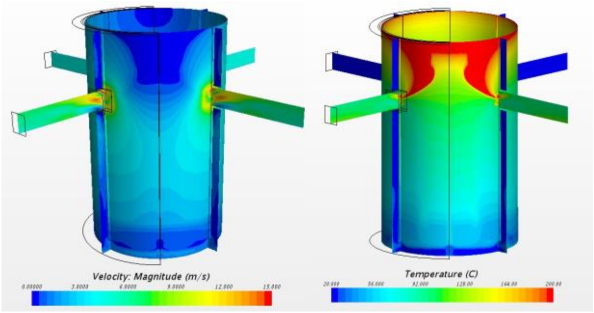


Fig. 8. Velocity (left) and Temperature (right) distribution when *L* = 9m.

3. CFD Simulation

Based on the result of 1D code analysis, 3D CFD simulations are conducted with the duct level variation using commercial CFD software STAR-CCM+. The CFD simulations are conducted on the air path, outside of CV, and the CV temperature that obtained from 1D code analysis is used as a thermal boundary condition. Fig. 7 and 8 show the velocity and temperature distribution of upstream air for the duct level of 13.7m and 9m, respectively. For the case of low duct level as shown in Fig. 8, it is observed that the air velocity is very low at the upper side of duct and hot spot is observed at that region. This can cause excessive thermal stress and reduce the structural reliability of the system. However, in the point of RV support structure, it is recommended to lower the duct level. Because of these conflict requirements, the hotspot avoidance design is conducted as shown in Fig. 9. The arrangement of inlet and outlet ducts is changed symmetrically. As a result, the hotspot is not observed although the ducts are located at low position.

4. Conclusion

In this paper, the heat removal performance of RVCS is evaluated depends on the duct level using PARS2-LMR code and commercial CFD program for optimum design of RVCS to satisfy both conflicting needs,

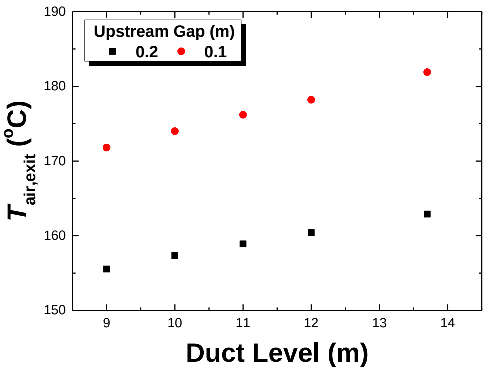


Fig. 6. Exiting air temperature with duct level variation

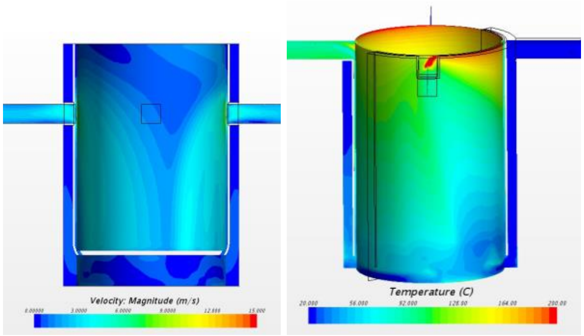


Fig. 9. Velocity (left) and Temperature (right) distribution when *L* = 9m with symmetry injection.

structural reliability and cooling performance. As a result of PARS2-LMR code analysis, it was observed that the heat removal rate increases as increase of duct level and the geometrical conditions, that satisfy the design limitations, were obtained. To qualitatively observe the trends of local temperature distribution, CFD simulations were conducted and hotspots were observed at the upper region of ducts for the low duct level case. As a hotspot avoidance design, the inlet and outlet directions are changed to symmetrical structure and the hotspot does not occur at this design. It is expected that the results of this paper will contribute to the concept design of PGSFR RVCS and will be used as a research material.

ACKNOWLEDGEMENT

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