Transactions of the Korean Nuclear Society Virtual Autumn Meeting
October 21-22, 2021

Preliminary study on a reactor vault cooling system using the TRACE code

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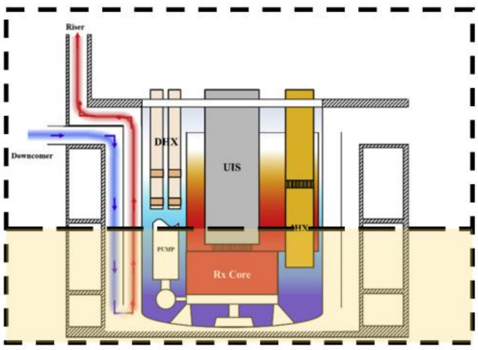
1. Introduction

A prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) which is under development by Korea Atomic Energy Research Institute (KAERI) uses liquid sodium as coolant [1]. Therefore, the emergency injection strategies which is commonly used in PWRs cannot be adopted. Therefore, the safety systems which removes decay heat passively are essential. Although the passive decay heat removal system (PDHRS) which passively removes decay heat is installed, to cope with accident when PDHRS fails due to sodium solidification and external events, additional means of passive safety system should be considered. Therefore, the reactor vault cooling system (RVCS) which cools the external surface of containment vessel via natural convection of air is introduced [1]. The detailed schematic diagram of the RVCS was shown in Fig.1.

As the heat removal performance of the RVCS can affect the safety of the PGSFR in severe accident, it should be analyzed. The decay heat removal via RVCS is conducted by two heat transfer mechanisms: natural convection heat transfer and radiation heat transfer. The former occurs as the heated air around the containment vessel (CV) flowed out of the RVCS outlet, and the relatively cool air flowed into the RVCS inlet to continuously cool the CV. The radiation heat transfer occurs between the RV-CV and CV-air separator. Thus, it is essential to consider both natural convective heat transfer and radiation heat transfer to properly predict the heat removal performance of the RVCS.

The purpose of this paper is to provide an insight for modeling the lower part of RVCS with the TRACE code, in particular, the natural convection and radiation heat transfer. To validate the model, we benchmark the experiments performed at Incheon National University [2-3].



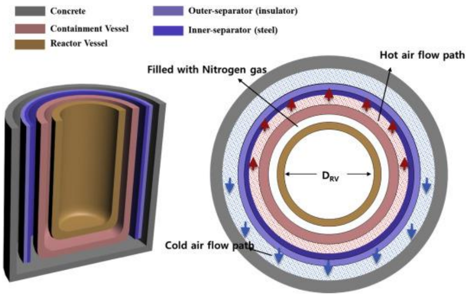


Fig.1 Schematic diagram for PGSFR and RVCS

2. Development model using TRACE code

The natural circulation experiments for the lower part of RVCS are performed at Incheon National University to identify heat transfer characteristics [3]. The experiment apparatus is 1/4-th of the original PGSFR, which is scaled down using the Ishii-Kataoka scaling method.

As shown in Fig. 2, heaters are installed on the heat plate cover to make a constant heat flux along the curved surface (heating section). The elevation of the inlet and outlet was the same, and the temperature of air and wall (e.g., CV, separator, bottom) are measured at various points. The initial and boundary conditions used in the analysis are summarized in Table 1.

Table.1 Input data for TRACE code simulation

	Experiment	TRACE-code
Volume	0.25 [m^3]	0.25 [m^3]
Heat rate	3821.28 [W]	3821.28 [W]
Inlet air temperature	295.12 [K]	295.12 [K]
Outlet mass flow rate	0.047 [kg/s]	0.047 [kg/s]
Initial pressure	101.325 [KPa]	101.325 [KPa]

2.1 Nodalizations for TRACE code

Fig. 3 and 4 show the nodalizations for the lower part of the RVCS and 3-D vessel component, respectively. In the model, 1-D pipes are used to simulate inlet and outlet. Also, containment vessel (CV) is modeled as a 3-D vessel component in cartesian geometry. The vessel has 9 levels in the axial direction and 12 cells in the horizontal direction. The curvature of the CV was simulated by adjusting the volume fraction of cells in a stair shape.

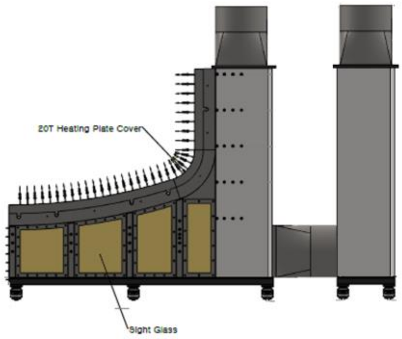


Fig.2 Schematic diagram of experimental apparatus for low-channel of RVCS

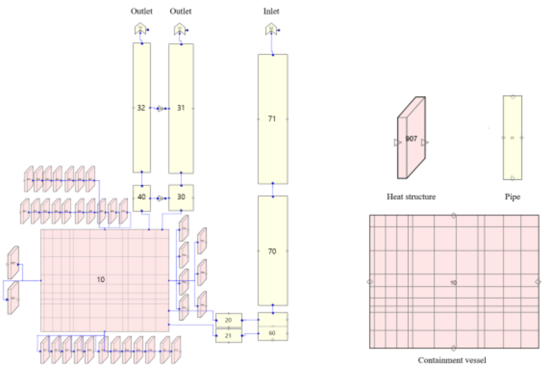


Fig.3 TRACE code nodalization for RVCS

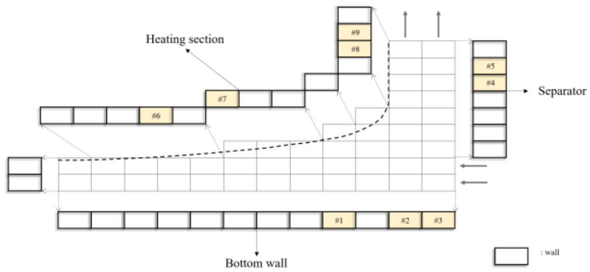


Fig.4 Detailed diagram of 3-D vessel component

2.2 Heat Transfer models

Both convection and radiation heat transfer should be considered to calculate the performance of the RVCS. The TRACE code automatically calculates convection heat transfer. The heat transfer coefficient is evaluated using the Nusselt number ($\mathrm{h} = \mathrm{k_w Nu/L}$), which is calculated according to the Mcadams correlation [4]:

$$Nu = 0.13 \cdot (Gr_a \cdot Pr_w)^{1/3} \tag{1}$$

where the Grashof number and Prandtl number are:

$$Gr_a = \frac{g \cdot \beta_a \cdot (T_w - T_a) \cdot L^3}{\left(\frac{\mu_W}{\rho_{ref}}\right)^2} \tag{2}$$

$$Pr_w = \frac{\mu_w C p_w}{k_w} \tag{3}$$

ρ_{ref} is the air density evaluated at a reference temperature, which can be calculated as follows:

$$T_{ref} = \frac{1}{2} \cdot (T_w + T_a). \tag{4}$$

To consider the radiation heat transfer, a user must provide values for the view factor and emissivity. The equation for calculating radiation heat transfer is as follows:

$$q_{rad} = \varepsilon \sigma A_i F_{ij} (T_i^4 - T_j^4) \tag{5}$$

$$\sigma = 5.6703 \times 10^{-8} \tag{6}$$

2.2.1 View factor

The view factor $\mathrm{F_{ij}}$ is defined as the fraction of the radiation leaving surface i that is intercepted surfaces A_i and A_j [5].

$$\mathrm{F_{ij}} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{cos\theta_i cos\theta_j}{\pi R^2} dA_i dA_j \tag{7}$$

The view factor used in the analysis was calculated using the Nusselt's unit sphere method.

$$\mathrm{dF_{ij}} = \frac{cos\theta_i cos\theta_j dA_i dA_j}{\pi R_{ij}^2} \tag{8}$$

2.2.2 Emissivity

The Emissivity (ε) is defined as the ratio of radiation radiated from the actual surface to the radiation emitted from the black body at the same temperature. Emissivity is a function of wavelength, angle, and temperature.

$$\varepsilon \equiv \varepsilon\,(\lambda, \theta, \phi, \mathrm{T}) \tag{9}$$

However, TRACE code uses the total hemispherical emissivity, which represents the mean value of emissivity for all possible angles (θ, ϕ) and wavelength (λ). That is, the angles and wavelength could be negligible. Thus, the emissivity is a function of temperature only, as below:

$$\varepsilon \equiv \varepsilon\,(\mathrm{T}) \tag{10}$$

The walls of the experimental facility made of stainless steel, and the emissivity range is 0.1 to 0.95. The sensitivity test for the emissivity is performed. In TRACE code, the emissivity can be entered as a constant value or the function of temperature. Therefore, four emissivities, $\boldsymbol{\varepsilon}$ = 0.2, 0.5, 0.8, 0.9, and a correlation (Eq. (11)), are tested. The correlation ($\boldsymbol{\varepsilon(T)}$) is obtained by fitting the equation to the graph presented in a previous study [5], and the equation is as follows.

$$\varepsilon(\mathrm{T}) = 0.08517 + 1.34037 \times 10^{-4} \times T + 1.28503 \times 10^{-7} \times T^2 \quad (11)$$

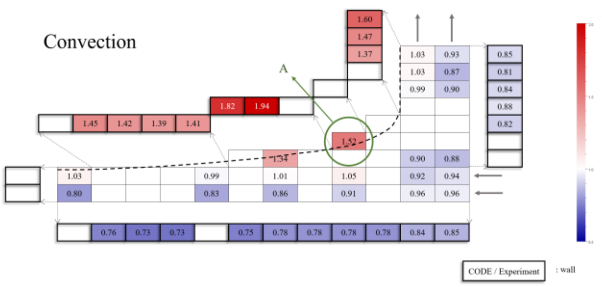
Table 2 shows the sensitivity analyses results. Emissivity does not significantly affect the wall temperature. As shown in Table 2, as the emissivity as a function of temperature shows minimum error, the emissivity as a function of temperature, which is specified above, is used for modeling the RVCS.

Table.2 Average error of wall temperature according to emissivities

emissivity	0.2	0.5	0.8	0.9	correlation
Avg.error [%]	12.2	15.3	16.4	16.6	10.8

3. Results and discussion

Fig.5 shows the ratio ($\mathbf{T_{CODE}/T_{EXP}}$) of the code value to the experimental value. The model with radiation heat transfer results in reduced errors in overall. The wall temperature of the heating section becomes lower and the bottom wall and air separator temperature becomes higher due to the radiation heat transfer. By accounting the radiation heat transfer, the wall temperature increases, which enhances convection heat transfer, reducing the error of the air temperature. As shown in Table 3, in the model that only considers convective heat transfer, the average error is 22% while the model with both convection and radiation heat transfer have an average error of 8.7%.



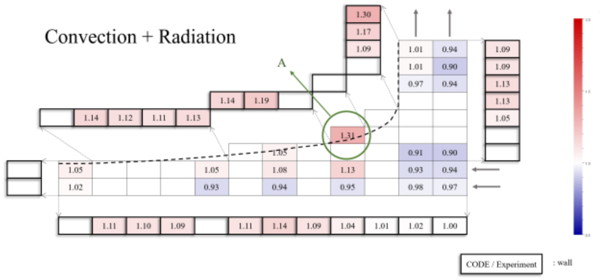


Fig.5 Comparison between the model and experiment.

Table.3 Average temperature error at components

Component	Convection [%]	Convection + Radiation [%]
Heating section	54.1	14.5
Bottom wall	22.3	7.1
Separator	15.9	9.8
Air	9.7	6.9
Outlet	1.1	1.1
Average	22	8.7

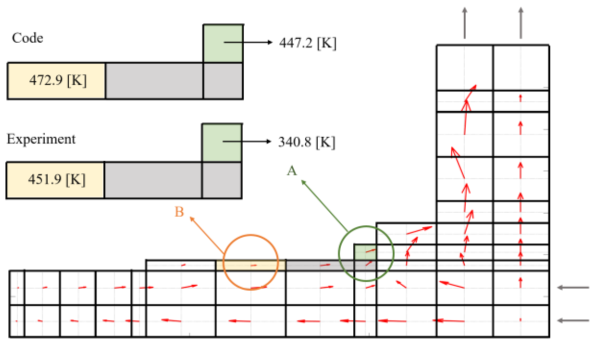


Fig.6 Vector field indicating mass flowrate

As shown in Fig.5, regardless of the consideration of radiation heat transfer, the air temperature at point A showed the largest error.

The temperature difference between points B and A is greater in the experiment compared to that of code. The code to experiment air temperature difference at point B shows relatively smaller difference than that of point A, which insists that the heat exchange in wall to air is calculated with moderate error.

The larger error at point A is thought to be attributed to the estimation of mixing rate in TRACE code. It can be recognized in the vector field in Fig. 6 that, the air coming from the inlet rises to point A due to buoyancy force. Thus, the mixing of cold air from the inlet and hot air supplied along the heated surface results in lower air temperature in experiment at point A. However, the underestimation of mixing rate in TRACE code results in higher air temperature at point A.

4. Conclusion

In this paper, we conducted the modeling about the lower part of RVCS and confirmed that the TRACE code can properly predicts the heat removal performance of RVCS through the comparison with the experimental data. The radiation heat transfer must be considered, as the surface temperature of CV is high enough to produce radiation heat transfer. When the radiation heat transfer is taken into the account, the average error of CV wall temperature is reduced to 14.5 %, which is huge reduction compared to convection-only case (average error of 54.1 %).

Through sensitivity analysis on emissivity, it is confirmed the wall temperature is not so sensitive on the emissivity. Although the emissivity of wall is commonly considered as a constant value for practical reasons, usage of emissivity as a function of temperature enhances the accuracy of radiation heat transfer evaluation.

The analysis results could be used as a guideline of thermal-hydraulic analysis for RVCS.

NOMENCLATURE

T	Temperature [K]
L	Length [m]
g	Gravitational acceleration $[\mathrm{m/s^2}]$

Greek symbols

β	Thermal expansion ratio [1/K]
μ	Viscosity $[\mathrm{N \cdot sec/m^2}]$
ρ	Density $[\mathrm{kg/m^3}]$
k	Thermal conductivity $[\mathrm{W/m \cdot K}]$
Cp	Specific heat $[\mathrm{J/kg \cdot K}]$

Subscripts

a	Air
w	Wall
ref	Reference
conv	Convection
rad	Radiation

ACKNOWLEDGEMENTS

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT and Future Planning) (No. NRF-2017M2A8A4018582)

REFERENCES

[1] J. Yoo, J. Chang, J.-Y. Lim, J.-S. Cheon, T.-H. Lee, S.K. Kim, K.L. Lee, H.-K. Joo, Overall system description and safety characteristics of prototype Gen IV sodium cooled fast reactor in Korea, Nuclear Engineering and Technology 48 (2016) 1059-1070.

[2] Koung Moon Kim, et al., Design of A scale-down experimental model for SFR reactor vault cooling system performance analyses, department of Mechanical Engineering, Nuclear Engineering and Technology 52 (2020) 1611-1625

[3] D.-W. Jerng, Y-G Lee, B-J. Yun, et al., A study on heat transfer model and performance of Passive systems for nuclear power plant containment cooling, National Research Foundation of Korea, 2015

[4] W.H. McAdams, Heat Transmission, 3rd ed., McGraw-Hill, New York, 1954, Chap.7

[5] Frank P. Incropera, Fundamentals of heat and mass transfer, 7th ed., John Wiley & Sons, Chap.12