Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Effect of air cooling performance on the temperature distribution of the reactor pool under RVACS operation

Min Ho Lee [a], Dong Wook Jerng[b], In Cheol Bang [a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)*
, 50 UNIST-gil, Ulju-gun, Ulsan, 44919, Republic of Korea
[b]*School of Energy Systems Engineering, Chung-Ang University,*
84 Heukseok-ro, Dongjak-gu, Seoul, 06974, Republic of Korea
[*]*Corresponding author: icbang@unist.ac.kr*

1. Introduction

Reactor vessel auxiliary cooling system (RVACS) is the one of the passive safety systems which could be applied to the liquid metal-cooled reactor. Heat removed by the conjugated heat transfer between the natural circulation inside the pool, and the other natural circulation of the air, which is connected to the atmosphere. Prototype generation-IV sodium-cooled fast reactor (PGSFR) also adopted RVACS as decay heat removal system [1]. Most of the researches about RVACS have been conducted focusing on the heat removal capacity, in other words, external air circulation [1 - 4]. For the natural circulation of the reactor pool, researches about direct heat removal system (DHRS) could be referred for the similarity law. Takeda et al. suggested modified dimensionless parameter as modified Grashof number and modified Boussinesq number for natural circulation of liquid metal [5]. This similarity law was validated through experiment by Lee et al. [6] and through CFD by Ieda et al. [7].

In so far, there has been no researches about the natural circulation of the reactor pool. Different to DHRS, natural circulation flow path of the RVACS is same with that of normal operation, including intermediate heat exchanger (IHX), pump and inlet piping, and the core. Therefore, it should be investigated to evaluate exact performance RVACS, including evaluation of the safety margins like reactor vessel (RV) temperature or sodium temperature. However, boundary condition for the reactor pool natural circulation was not investigated at all. Conjugated boundary between internal reactor pool, and external air natural circulation was just assumed as constant temperature or simply modeled as 1-D [1 - 4] in the researches related to external air cooling. For the reactor pool natural circulation, even natural circulation under RVACS has not analyzed sufficiently, as well as the effect of the boundary condition, which is still unknown and can be varied by change of external air cooling condition.

To investigate the effect of change of external air cooling on the temperature distribution inside the reactor pool under RVACS operation, SINCRO-2D facility has been designed in UNIST, which is the abbreviation of SImulating Natural Circulation of Sodium pool under RVACS Operation - 2D. Change of the cooling capacity of the external air circulation was introduced as temperature gradient between the RV top and the bottom

2. Experimental methods

SINCRO-2D facility was designed based on the similarity law, focusing on the temperature distribution. In this section, similarity law and design parameter of the SINCRO-2D were briefly introduced. And then, test matrix to investigate boundary condition effect was discussed.

2.1 Similarity analysis

The first step of the similarity is deriving important parameter for the similarity. In present study, non-dimensionalization of the governing equation was used and corresponding non-dimensional numbers were derived. However, in case of natural circulation, time, temperature, and pressure cannot be represented by external references. Here, reference pressure difference was omitted because it could be derived from the reference velocity. These reference parameters were derived from the characteristics of the natural circulation; balance between buoyant potential energy and kinetic energy (1), and that between heating rate and energy conversion (2).

$$\rho g\beta \Delta TL = \frac{1}{2}\rho u_{ref}^{2} \qquad (1)$$

$$u_{ref}\frac{\partial T}{\partial x} \sim \frac{Q_0}{\rho c} \qquad (2)$$

After that, temperature difference terms in natural convection could be replaced into combination of system properties and material properties.

$$u_{ref} = \left(\frac{\beta g}{\rho c L}\right)^{1/3} Q^{1/3} \qquad (3)$$

$$\Delta T_{ref} = \left(\beta g \rho^2 c^2 L^5\right)^{-1/3} Q^{2/3} \qquad (4)$$

$$t_{ref} = \left(\frac{\rho c L^4}{\beta g}\right)^{1/3} Q^{-1/3} \qquad (5)$$

Using these reference parameters, mass, momentum, and energy conservation equation could be non-dimensionalized as following equations.

$$\frac{\partial u_i *}{\partial x_i *} = 0 \qquad (6)$$

$$\frac{\partial u_i *}{\partial t *} + u_j * \frac{\partial u_i *}{\partial x_j *} = \frac{1}{Gr'^{1/2}} \frac{\partial^2 u_i *}{\partial x_j^2 *} - T * \delta - \frac{\Delta P *}{\rho u_0^2} \frac{\partial P *}{\partial x_i *} \qquad (7)$$

$$\frac{\partial T *}{\partial t *} + u_j * \frac{\partial T *}{\partial x_j *} = \frac{1}{Bo'^{1/2}} \frac{\partial^2 T *}{\partial x_j^2 *} + 1 \qquad (8)$$

Here, the important non-dimensional numbers, which was modified Boussinesq number (Bo') and modified Grashof number (Gr') have been derived, as in the equation (9) and (10).

$$Gr' = \left(\frac{\beta g}{\rho c}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\nu^2} \qquad (9)$$

$$Bo' = \left(\frac{\beta g}{\rho c}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\alpha^2} \qquad (10)$$

Bo' represents ratio between heat transfer by natural circulation and by conduction, which is similar to Peclet number in forced convection. Gr' means ratio between inertial force by buoyancy and viscous force, which is similar to Reynolds number.

Object of the SINCRO-2D experiment was simulate temperature distribution of the reactor pool. Between Bo' and Gr', for simulating temperature distribution, it was known that Bo' is more important that Gr'. Gr' is related to natural circulation flow regime, such as laminar or turbulent. Moreover, concentrating on Bo' could provide rough similarity for the flowrate. Therefore, in this experiment, Bo' was considered as the core similarity parameter.

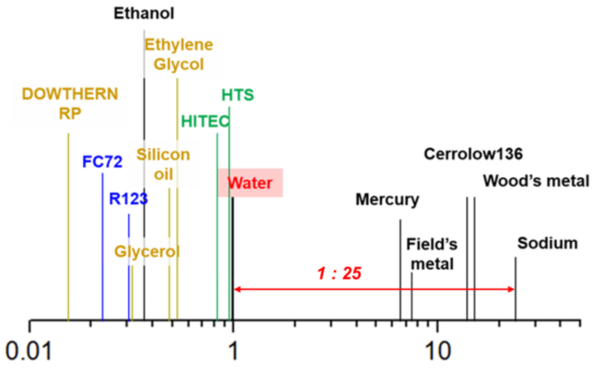

Fig. 1. Relative length scale to have identical Bo'

Figure 1 represents various materials' relative length scale for the identical Bo'. Various groups of the non-metallic fluid were considered for the simulant of the original coolant, sodium, water was the best simulant for its transparency, handling, distortion of the scale, and etc. Corresponding length scale difference between the original sodium reactor and SINCRO-2D water facility was 1 : 25.

2.2 SINCRO-2D Facility

Based on the Bo' based similarity law, SINCRO-2D was designed as two-dimensional slab model, in 1/25 scale of the original reactor, PGSFR. Gap between the two slabs was 50 mm. As length scale was reduced in 1/25 scale, height and radius were decreased to 1/25 of the original reactor. Reference temperature difference, which means the conversion ratio of the temperature distribution in the pool, was 6.61 : 1. All these parameter and ratio were summarized in the table 1.

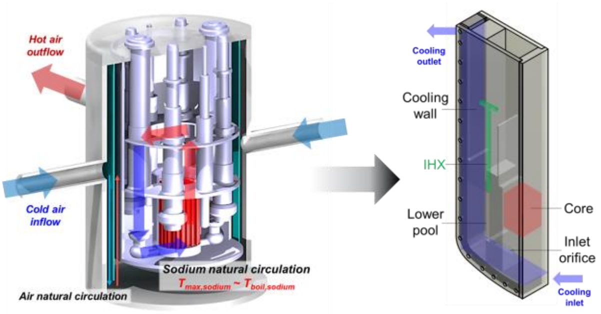

Fig. 2. Schematic of the SINCRO-2D

Table I: Specification of the SINCRO-2D

Parameter	PGSFR	SINCRO-2D	Ratio
Radius	4.3 m	173 mm	1/25
Height	15.3 m	540 mm	1/25
Q’’’	213.4 W/cm^3	213.4 W/cm^3	1
ΔT_{ref}	1.091 ^{o}C	0.165 ^{o}C	6.61

Characteristics of the RVACS operation were reflected into SINCRO-2D design. Heating in the SINCRO-V was given as power level like decay heat in the reactor. And cooling was achieved by the temperature boundary condition, which is conjugated to external air cooling.

2.3 Test matrix for boundary condition

If external air cooling condition was changed, flow rate of the air changes. Change of the flow rate could be represented by the temperature difference between the inlet and outlet of the air. In the viewpoint of CV, temperature difference between its top and the bottom was increased. It is the same to RV, which is cooled by radiation heat transfer to CV and is boundary condition for the reactor pool natural circulation at the same time. Therefore, change of the air cooling condition was simplified as temperature difference between the top and the bottom of the RV.

There has been no full result for the temperature distribution of the RV under RVACS operation. Therefore, to predict possible range of the temperature difference of the top and the bottom of the RV, literature survey was conducted, and its results were summarized in the table II.

Table II: Possible range of the ΔT between the top and the bottom of the RV

Condition	**ΔT_PGSFR**	**ΔT_SINCRO**	**θ by ΔT_{ref}**
Natural circulation (estimated)	88°C	13.3°C	53.8 times
Air inlet & outlet	135 - 160°C	20.4-24.2°C	82-97 times
Normal operation	155.0°C	23.48°C	94.7 times
Max dT in the experiment	174.8°C	26.49°C	106.8 times

From the literature, it could be concluded that possible temperature difference between the RV top and bottom was 50 - 100 times of the ΔT_{ref}. Therefore, the experiments were conducted under 40, 60, 80, and 100 times of the ΔT_{ref} condition, while decay heat of the core was fixed as 1%, corresponding to 200 W.

3. Results and Discussion

Temperature distribution of the SINCRO-2D was illustrated in the figure 3. Unlike other safety systems like DHRS, there was no significant severe thermal stratification. Hot region was generated after the core, until the T-junction of the IHX. In the narrow gap in the hot pool, stacked temperature distribution was observed. Between the IHX and narrow gap, if conduction was dominant heat transfer mechanism, the amount of transferred heat through the narrow gap could be calculated by simple 1-D conduction equation. However, only 0.08 W of the heat was transferred by the conduction, using the given temperature difference, 52°C and 35.2°C. However, the temperature of the pool was changed from the 52 °C to 47.6 °C. It is too small amount to make such cooling, compared to its power, 200 W. Thus, natural circulation was even dominant heat transfer mechanism in the narrow gap.

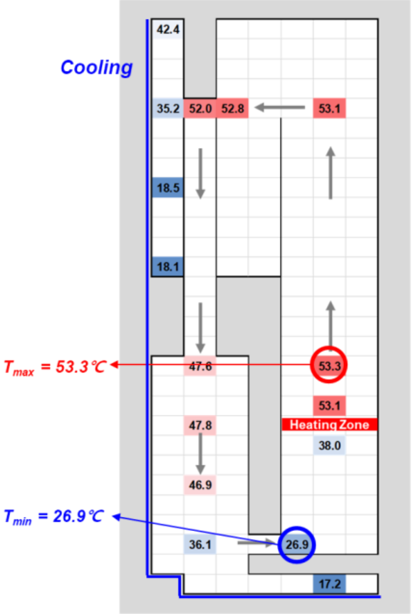

Fig. 3. Representative temperature distribution in the SINCRO-2D (1% decay heat, B.C. = 60ΔT_{ref})

Temperature in the lower pool showed interesting distribution. As vertical location comes downward, temperature did not change significantly and rapidly changed at the two bottom points. If the effect of flow on the temperature distribution is insignificant, temperature at the same height showed similar value. However, temperature in the lower plenum showed a profile strongly depended on the downward flow from the IHX. It means that temperature profile could be changed by the velocity profile, and a three-dimensional facility is required to observe three-dimensional flow distribution at the lower plenum, especially between the IHX outlet and pump inlet.

Concentrating on the temperature change history along the natural circulation path, hot coolant just after the core was 53.1°C. After the IHX, it cooled down to the 47.6°C by the cooling through the narrow gap, and finally cooled down the the 26.9°C by the cooling through the lower plenum, which was observed at the inlet piping. Only 4.5°C of the temperature decreased by the narrow gap cooling, and 20.8°C of the temperature decreased by the cooling at the lower plenum. Therefore, it could be concluded that 79 % of the cooling was achieved through the lower plenum.

To observe the effect of the boundary condition on the temperature distribution, temperature at the selected points were summarized in the figure 4. Temperature showed upward or downward shifted profile with different boundary conditions. Change of the shape of the temperature distribution was not observed in the current experiment. Change of the boundary condition was global increase or decrease of the temperature in the whole pool. In other words, similar heat removal characteristics were observed regardless to boundary condition, such as heat removal fraction and heat transfer regime in the narrow gap. In the aspect of predicting maximum temperature in the pool, boundary condition effect could be simplified as additional temperature increase in the pool and it was same to overall temperature distribution.

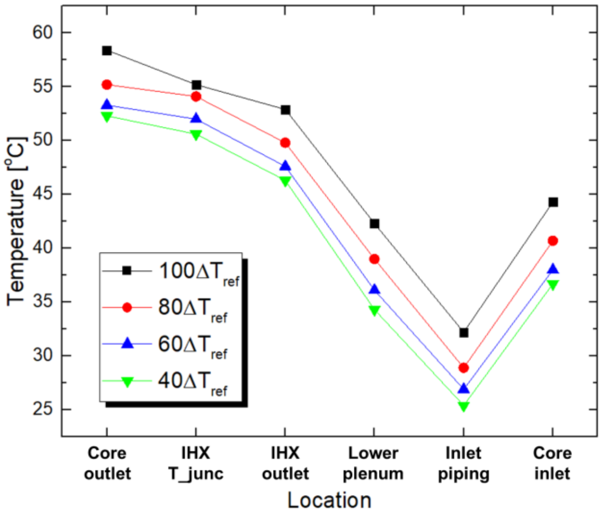

Fig. 4. Temperature at the selected location with different boundary condition

4. Conclusions

Effect of the boundary condition on the temperature distribution in the reactor pool under RVACS operation was experimentally studied. Boundary condition was simplified as temperature difference of the top and the bottom of the RV and its range was determined. Natural circulation prevented severe thermal stratification and importance of the 3D effect was observed by flow dependent temperature profile. Stacked temperature at the narrow gap in the hot pool and the dominant heat transfer mechanism in the narrow gap was natural circulation, despite of its size. Main cooling was achieved in the lower plenum. Regardless to boundary condition, temperature distribution inside the pool showed identical tendency. In other words, boundary condition effect on the maximum temperature and overall temperature distribution could be simplified as one additional term.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Energy Research Program and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT) (No. 2017M2A8A4043539, No. 2017M2A8A2018595)

REFERENCES

[1] C. W. Choi, T. K. Jeong, and S. J. An, Thermal-hydraulic analyses of passive reactor vault cooling system (RVCS) in PGSFR using MARS-LMR. Annals of Nuclear Energy, Vol. 117, p. 333, 2018.

[2] P. Song, D. Zhang, T. Feng, S. Wang, J. Chen, X. Wang, X. Xue, Y. Zhang, M. Wang, S. Qui, and G. H. Su, Numerical approach to study the thermal-hydraulic characteristics of Reactor Vessel Cooling system in sodium-cooled fast reactors, Progress in Nuclear Energy, Vol. 110, p. 213, 2019.

[3] S. J. Yeom, S. H. Ryu, D. H. Kim, and T. H. Lee, The Effect of Duct Level on the Performance of Reactor Vault Cooling System in the PGSFR, Transactions of the Korean Nuclear Society Autumn Meeting, Oct. 29-30, Gyeongju, Korea 2015.

[4] S. H. Ryu, The Effect of Duct Level on the Performance of Reactor Vault Cooling System in the PGSFR, Transactions of the Korean Nuclear Society Autumn Meeting, Oct. 29-30, Gyeongju, Korea 2015.

[5] H. Takeda, T. Koga, and O. Watanabe, Experimental and computational simulation for natural circulation in an LMFBR, Nuclear Engineering and Design, Vol. 140, pp. 331, 1997.

[6] M. H. Lee, D. W. Jerng, and I. C. Bang, Experimental Validation of Substitutability of the Liquid Metal Natural Circulation using Water, Proceedings of NTHAS-11: The Eleventh Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, November 18-21, Busan, Korea, , 2018.

[7] Y. Ieda, H. Kamide, H. Ohshima, S. Sugawara, and H. Ninokata, Strategy of Experimental Studies in PNC on Natural Convection Decay Heat Removal, IAEA-IWGFR Specialists' Meeting, 1993.