Integrated experiment for RVACS with combination of two different similarity law

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1. Introduction

The RVACS, which is an abbreviation of the reactor vessel auxiliary cooling system, is a decay heat removal system having a lot of advantages. It was first adopted in the PRISM [1]. Decay heat from the core is transferred to the RV by natural circulation of the reactor pool, and it cooled by the external air natural circulation. Lower reactor vessel (RV) temperature could provide negative reactivity in terms of the safety shutdown. The RVACS operates by the natural circulations, thus, it is passive and robust. According to the concept itself, which is decay heat removal through the RV, the RVACS could be applied to various types of the reactors.

It was also applied to the prototype gen-IV sodium-cooled fast reactor (PGSFR) in Korea [2]. Here, main safety parameters were the maximum coolant temperature, which is related to sodium boiling, and the RV temperature, which is related to RV creep failure. RVACS were mainly analyzed by numerical way. RVACS on the PGSFR was analyzed using MARS and CFD [3]. Main concerns were coolability of the air natural circulation. Choi et al. analyzed performance of the RVACS with various activation time [4]. RVACS showed significant could keep the sodium coolant from boiling. The RVACS in Lead-cooled fast reactor was also analyzed [5].

However, numerical analysis should be conducted based on the validated model and code. They should be validated against experiments. Regard to the experiment, they were mainly conducted as separated experiment for in-vessel reactor pool natural circulation, and ex-vessel air natural circulation. For reactor pool, simulating experiment were generally selected for safety and economy, and simulant was water. In 2-D geometry, effects of decay heat level and cooling boundary were observed by Lee et al. [6]. For external duct, Kim et al. designed experimental facility and analyzed velocity and temperature distribution in the air duct [7]. These separated experiments were based on the steady state analysis.

However, safety analysis is intrinsically transient and integrated. Therefore, to give data for strict validation of the code, integrated and transient experiments for in- and ex-vessel should be conducted. In this paper, integrated and transient experiment were analyzed. Bo' based similarity law and Ishii's similarity law were adopted for in- and ex-vessel, respectively. Steady state under RVACS operation, and transient from normal operation were simulated.

2. Experimental method

Design of the experimental facility, corresponding similarity law, and test matrix were discussed in this section. The experimental facility was named as SINCRO-IT, which is an abbreviation of **SI**mulating **N**atural **C**irculation of reactor pool in **R**VACS **O**peration – **I**ntegrated and **T**ransient.

2.1 Similarity law

For inside of the RV, natural circulation of the sodium was simulated focusing on the temperature distribution. Therefore, modified Boussinesq (Bo') based similarity law was employed. There are three main non-dimensional numbers; Bo', modified Grashof number, and the Euler number. They were summarized in equation (1) – (3). Bo' means the ratio of the heat transferred by natural circulation to that by the conduction. Therefore, Bo' could represent characteristics of temperature distribution under natural circulation. Gr' is the ratio of the buoyant force to inertial force, thus, it could represent the flow regime. Eu is an independent number which means pressure drop of each component in the system.

$$Bo' = \left(\frac{\beta g}{\rho c_p}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\alpha^2} \quad (1)$$

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

$$Eu = \xi = \frac{2\Delta P}{\rho u_{ref,system}^2} \quad (3)$$

Bo' and Gr' have many parameters in common. Therefore, it is hard to modify one number while the other number is fixed. They were coupled each other, thus, it should be selected either Bo' or Gr'. It was experimentally validated that Bo' is more important to have similarity of the temperature distribution, and the error in the simulating experiment was 27 % in maximum [8].

Regard to ex-vessel air natural circulation, well-known Ishii's similarity law was employed [9]. Key similarity parameters were summarized below.

$$Ri = \frac{g\beta \Delta T_0 L_0}{u_0^2} \quad (4)$$

$$F_i = \left(\frac{f_l}{d} + K\right)_i = Eu \quad (5)$$

$$St_i = \left(\frac{4hL_0}{\rho c_p u_0 d}\right)_i \quad (6)$$

Unlike Bo' based law, Ri was not assumed as unity in the Ishii's law like equation (4), which express ratio of natural circulation driving force to flow inertia. Friction number is exactly same with Eu, pressure drop coefficient. Modified Stanton number (St in equation 6), which describes ratio of wall convection and axial convection, is core non-dimensional number for similarity of fluid heat transfer. In the aspect of natural circulation of the external air, Ri, St, and friction number were main similarity parameters. The friction number could be changed independently. Therefore, scaling of the experimental facility was conducted considering Ri and St.

2.2 SINCRO-IT facility

The SINCRO-IT facility was designed based on the PGSFR. It was simplified as 2-D slab model like Fig. 1, however, characteristics were kept. Core was simulated as a group of the cartridge heaters, and redan was also simulated. To simulate heat removal through intermediate heat exchanger (IHX) under normal operation, heat exchanger was added. It cools the Wood's metal pool by evaporation of the coolant, which makes steam at the outlet of the HX. Air cooling channel was attached on the wall simulating RV. The heater side, and frontal and posterior side of the experimental facility was insulated as concept of the slab model. Pump for the reactor circulation was left out in the facility.

The SINCRO-IT facility was designed to analyze both steady and transient state. Therefore, it is necessary to satisfy same time scale for in- and ex-vessel. The basic concept for time scale was in equation (7). In-vessel time scale was summarized in equation (8), while ex-vessel time scale was in equation (9).

$$t_0 = L_0 / u_0 \quad (7)$$

$$t_{ref,R} = \left(\frac{\rho c_p L_0^4}{\beta g Q}\right)_R^{1/3} \quad (8)$$

$$t_{0,fluid,R} = \left(\frac{\rho c_p d L_0}{2\beta g q''}\right)_R \quad (9)$$

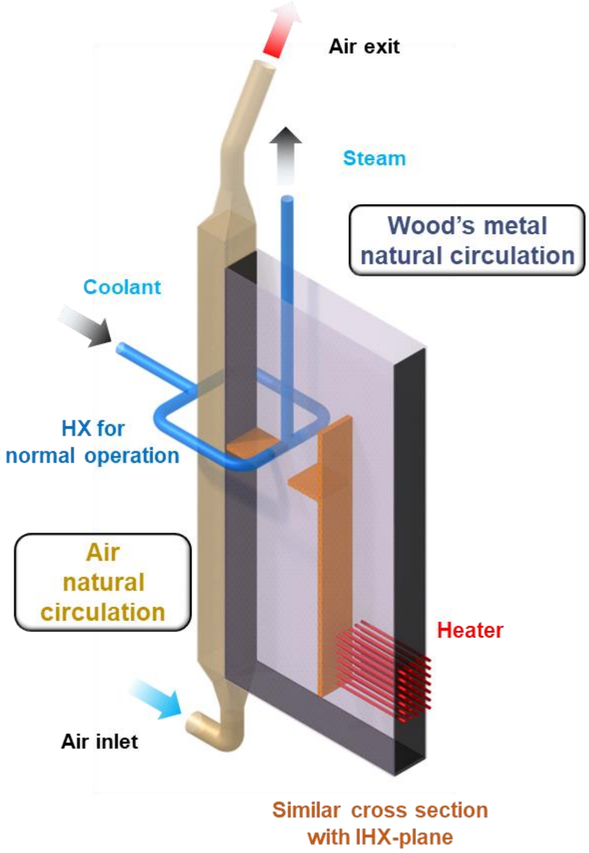

Fig. 1. Schematic of the SINCRO-IT

Both time scales could be represented by combination of the length scale and reference velocity, which were expressed as t_{ref} and t_0 for different similarity law. Subscript R means ratio of quantities inside the parenthesis.

Here, many parameters in common in equation (8) and (9), however, there are several differences. First, length scale was reduced isotopically in the Bo' based law, while there was d and L for length scale in Ishii's law. L represents height scale and d represents channel gap. Power for Bo' based law was treated as total power while heat flux was adopted Ishii's law. These two parameters could be easily translated to each other and basically same parameter. Therefore, time ratio could be treated as a function of material and length reduction ratio although there could be slightly changed by anisotropy. In- and ex-vessel time scales were made identical with proper length scale and simulant.

For in-vessel sodium, Wood's metal was selected as a simulant, while air was maintained for ex-vessel. This combination of the simulants was determined considering operating temperature, resolution of the data, handling, and overall scale of the facility. Combination of the Wood's metal and air does not make boiling or solidification issue under operation, and have enough resolution of the data with proper scale. SINCRO-IT was reduced from original PGSFR by 1 to 4 by length scale. Heat flux at the vessel wall was 1.0 kW/m^2, and it made time ratio of the facility 1 :

0.59. It means that 1 second in the SINCRO-IT corresponds to 0.59 second in the PGSFR. Temperature difference between the inlet and the outlet of the air channel was expected as 17.5 °C. St, which is a key similarity parameter for ex-vessel heat transfer was almost same between the prototype and the model. Ri was assumed as unity for in-vessel case, and showed perfect accordance for ex-vessel case. Although magnitude of the Bo' was differ as 1 : 10, however, it was still reasonable. Bo' was in the diffusion term in the non-dimensionalized energy equation, as form of $1/Bo'^{0.5}$, so its effect could be smaller than absolute value. The order of the Bo' was approximately 10^7, thus, it was still high, which makes diffusion term negligible, while it was reduced to 1 : 10. For these reasons, many other Bo' based facilities were established with more than 20 times of the differences [10]. Therefore, our ratio as 1 : 10 was reasonable, and thanks to compromise of the Bo' similarity, we could achieve good similarity for St and identical time ratio. Material properties were summarized in table I, and specification and similarity of the facility was summarized in table II.

Table I. Material properties

	Sodium	**Wood's metal**	**Air**
Melting point	98°C	80°C	-
Boiling point	883°C	766°C	-
Density	971 kg/m³	9500 kg/m³	1.23 kg/m³
Vol. therm. exp. coeff.	2.8e-4	2.5e-5	3.4e-3
Therm. cond.	65 W/m.K	13.5 W/m.K	0.025 W/m.K
Specific heat	1269 J/kg.K	190 J/kg.K	1012 J/kg.K
Viscosity	2.5e-4	4e-4	1.8e-5

Table II. Specification of the SINCRO-IT facility

	In-vessel	**Ex-vessel**
Original fluid	Sodium	Air
Simulant	Wood's metal	Air
Length scale	1 : 4	
Time ratio	1 : 0.59	
Wall heat flux	1.0 kW/m²	
Expected ΔT	-	17.5°C
St #	-	1 : 1.03
Ri #	1 : 1	1 : 1
Bo' #	1 : 10	-

2.3 Test matrix

The SINCRO-IT facility could manipulate external air flow rate like the PGSFR, while reactor pool only depends on the natural circulation. Under accident, external air flow rate was increased by damper opening. It could be simulated as simple increase of the flow rate by increasing blower power level. Therefore, external side could be sufficiently simulated just manipulating flow rate. Regard to in-vessel reactor pool, there are three main phenomena; decrease of the power, isolation of the IHX, and flow decrease by coastdown of the pump. Decrease of the power and could be simulated by cartridge heater. Isolation of the IHX could also be simulated by isolation of the cooling water in SINCRO-IT. However, coastdown of the pump and corresponding flow decrease could not be simulated because there is no pump in the SINCRO-IT. In summary, SINCRO-IT could simulate most of the phenomena in the PGSFR, except for coastdown of the flow rate.

Steady state analysis would be conducted for both normal operation and decay power with various power. It could be summarized as table III.

Table III. Test matrix and corresponding actions - steady

Status	**In-vessel**		**Ex-vessel**
	Power	IHX	Damper (air velocity)
Normal operation	100%, 50%	Activated	Closed (0.27 m/s)
Decay heat	10%, 5%, 2%	Isolated	Opened (1.57 m/s)

Based on the capability of the SINCRO-IT, test matrix was set as table III. Among the design basis events of the PGSFR, loss of heat sink (LOHS) could be simulated. Transient over power (TOP) under low power and re-criticality could also simulated by manipulating power. Loss of flow (LOF) and station black out (SBO) events could be partially simulated.

Table IV. Test matrix and corresponding actions - transient

Event	**In-vessel**			**Ex-vessel**
	Power change	IHX isolation	Coast -down	Flow increase
LOF	↓	O	X	O
LOHS	↓	O	X	O
SBO	↓	O	X	O
TOP*	↑	O	X	O
Re-cri.	↑	-	-	-

Among events, LOF, LOHS, SBO are very similar. Difference among the LOF, LOHS, and SBO are order of reactor trip and IHX isolation. These scenarios could be partially simulated except for pump coastdown. TOP could be partially simulated except for pump coastdown, and it would be limited to TOP at the low power operation due to limitation of the facility. * means experimental condition less than 100% of the normal operation power. Re-criticality at the decay heat level is expected as best-simulated scenario. Because it starts from

Results for the test matrix would be updated before presentation.

3. Summary and further work

To provide experimental results of RVACS for system code validation, SINCRO-IT facility was designed. It was integrated facility for both in- and ex-vessel, and had capability with transient experiment with identical time scale for both sides. Original working fluids, which are sodium and air was simulated as Wood's metal and air, respectively for in- and ex-vessel. Main similarity parameters for each domain (Bo' and St) were reasonably satisfied. In addition to the steady state analysis for normal operation and decay heat, various transient scenarios would be covered including LOF, LOHS, SBO, TOP, and re-criticality, except for pump coastdown.

NOMENCLATURE

c: heat capacity
d: gap size
g: gravitational acceleration
h: convective heat transfer coefficient
f: friction number
L: characteristic length
P: pressure
T: temperature
Q: total power
q": heat flux
t: time
u: velocity
x: length scale

α: thermal diffusivity
β: thermal expansion coefficient
δ: thermal boundary layer thickness
υ: kinematic viscosity
ρ: density

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REFERENCES

[1] A. Hunsbedt, and P. M. Magee, Design and performance of the PRISM natural convection decay heat removal system, Proceedings of international topical meeting of safety of next generation power reactors, May1-5, 1988, La Grange Park, IL.
[2] J. Yoo, J. Chang, J. Y. Lim, J. S. Cheon, T. H. Lee, S. K. Kim, K. L. Lee, and H. K. Joo, Overall System Description and Safety Characteristics of Prototype Gen IV Sodium Cooled Fast Reactor in Korea, Nuclear Engineering and Technology, Vol. 48, p.1059, 2016.
[3] S. Yeom, S. H. Ryu, D. Kim, and T. H. Lee, The effect of duct level on the performance of Reactor Vault Cooling System in the PGSFR, Proceedings of the Korean Nuclear Society Autumn Meeting, October 29-30, 2015, Gyeongju, Korea.
[4] C, Choi, T. Jeong, and S. 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.
[5] G. Wu, M. Jin, J. Chen, Y. Bai, and Y. Wu, Assessment of RVACS performance for small size lead-cooled fast reactor, Annals of Nuclear Energy, Vol. 77, p.310, 2015.
[6] M. H. Lee, D. W. Jerng, and I. C. Bang, Effect of air cooling performance on the temperature distribution of the reactor pool under RVACS operation, Transactions of the Korean Nuclear Society Autumn Meeting, Oct. 24-25, 2019, Goyang, Korea.
[7] K.M. Kim, D. H. Nguyen, G. H. Shim, D. W. Jerng, and H. S. Ahn, Experimental study of turbulent air natural convection in open-ended vertical parallel plates under asymmetric heating conditions, International Journal of Heat and Mass Transfer, Vol. 159, p.120, 2020.
[8] M. H. Lee, D. W. Jerng, and I. C. Bang, Experimental validation of simulating natural circulation of liquid metal using water, Vol. 52, p.1963, 2020.
[9] M. Ishii, I. Kataoka, Scaling Laws for Thermal-Hydraulic System Under Single Phase and Two-Phase Natural Circulation, Nuclear Engineering and Design, Vol. 81, p.411, 1984.
[10] A. Ono, A. Kurihara, M. Tanaka, H. Oshima, H. Kamide Study on Reactor Vessel Coolability of Sodium-Cooled Fast Reactor under Severe Accident Condition – Water Experiments Using a Scale Model -, Proceedings of ICAPP 2017, Apr. 24–28, 2017, Fukui and Kyoto, Japan