Integrated experiments for RVACS using combination of two different similarity law

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

The reactor vessel auxiliary cooling system (RVACS) is versatile and robust safety system. It operates by two natural circulations: in-vessel coolant natural circulation and ex-vessel air natural circulation. Therefore, it is a passive safety system, and its activation requires just opening of the damper at the air exit. Due to easy activation and passiveness, and its passiveness, the RVACS could be adopted for various reactor type.

Among the reactors, pool-type liquid metal reactors have advantages to apply RVACS. Large heat transfer area of the reactor vessel (RV), and favorable characteristics of the liquid metal coolant could make application of the RVACS easier and performance of the RVACS better. The protype Gen-IV sodium-cooled fast reactor (PGSFR) in Korea adopted RVACS as one of the decay heat removal system [1].

However, performance of the RVACS was not strictly evaluated. Because the RVACS has two natural circulations, which are conjugated at the RV, the RVACS has complicated heat transfer characteristics. For in-vessel natural circulation, the RV becomes cooling boundary, while the vessel surface is heating boundary for ex-vessel air natural circulation. These two natural circulations interact each other in real-time, transient experiment should be conducted for the performance evaluation of the RVACS.

For separated experiments, Lee et al. evaluated in-vessel natural circulation through simulating experiments [2], and Kim et al. conducted ex-vessel heat transfer experiments [3]. Therefore, separated experiments have been conducted for each side. Regard to the integrated analysis, there have been only numerical analysis. Yeom et al. showed effect of height of the air exit using system code MARS and CFD [4]. Choi et al. analyzed effect of activation time of the RVACS to the accident progression and contribution of the RVACS to the delay of the temperature rise [5]. However, there is no integrated experiments. To validate system code results and further safety analysis through the code, integrated experiment for the system code validation is required.

To conduct integrated and transient experiment for the RVACS performance evaluation, SINCRO-IT facility was designed with simulant, and several experiments were conducted under both steady and transient condition. Important safety parameters: the RV temperature and the maximum sodium temperature were evaluated based on the results of the simulating experiment in the SINCRO-IT.

2. Design of the SINCRO-IT

SINCRO-IT was designed with two-different similarity laws, which is an abbreviation of the Simulation of Natural Circulation under RVACS Operation – Integrated and Transient . Final goal of the experiments is to evaluate the RV and sodium temperature, therefore, Bo' based similarity law was employed for in-vessel, while Ishii's similarity law was employed for ex-vessel. The most important thing in the transient experiment with combination of the two different similarity law, is the identical time ratios for both laws. Considering similarity and time scaling ratio, for in-vessel sodium, simulant was selected as Wood's metal, and ex-vessel air was maintained as air with scale reduction [6]. Fig. 1 shows the schematic of the SINCRO-IT.

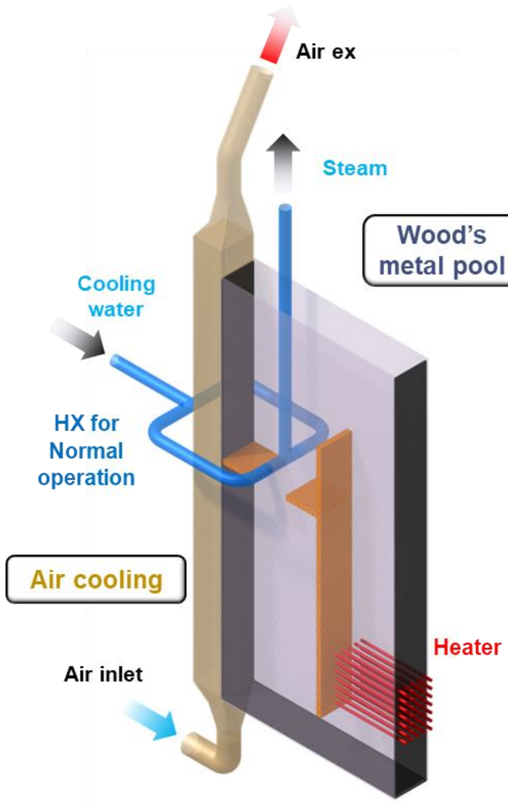

Fig. 1. Schematic of the SINCRO-IT

Table I: Specification of the SINCRO-IT

Parameter		**PGSFR**	**SINCRO-IT**	**Ratio [P/M]**
In-vessel	Bo’	8.14 x 10^7	7.56 x 10^8	0.093
	Power	280 kW	13.4 kW	20,900
	Radius	4.3 m	0.82 m	5
	Time ratio	**1**	**1.67**	**0.60**
Ex-vessel	St	0.119	0.116	1.026
	Ri	0.86	0.86	1
	Heat flux	14.5 kW/m^2	1 kW/m^2	14.5
	Height	6.7	1.68	4
	Ch. Width	0.3	0.4	0.75
	Time ratio	**1**	**1.69**	**0.59**

SINCRO-IT facility was designed to have similarity under natural circulation condition, so that primary pump was omitted for in-vessel. Therefore in-vessel only operates under natural circulation in the SINCRO-IT. Regard to ex-vessel, natural circulation flow rate was simulated by an equivalent flow rate by forced convection like Kim’s work [3].

Specification and similarity of the SINCRO-IT compared to its prototype PGSFR was summarized in Table 1. Strictly, SINCRO-IT simulated an arbitrary 2-D slab-shaped reactor, which has similar characteristics with the PGSFR. It was reduced as 1 : 4 to the prototype in terms of the length scale. Most important similarity parameter for in-vessel was modified Boussinesq number (Bo’) [7]. Its ratio between the prototype and model was approximately 0.09, however, it was still in a reasonable range. The time scaling ratio is 1.67 in the SINCRO-IT, which means that the time flow in the facility is slower than PGSFR by 1.67 time. 1 second in the PGSFR corresponds to 1.67 seconds in the SINCRO-IT.

For ex-vessel, the time scaling ratio was 1.69, which is very similar to that of the in-vessel. Important non-dimensional numbers for the heat transfer similarity were Stanton number (St) and Richardson number (Ri) [8]. Both St and Ri showed good accordance with the prototype. Heat flux was reduced as 1 / 14.5 for similarity, and channel width was rather slightly increased in the SINCRO-IT.

3. Experimental methods

3.1. Test matrix

There are two control variables in the SINCRO-IT facility. One is power, which is related to the decay heat level and the other is external air flow rate. Therefore, the test matrix would be composed of in-vessel power and ex-vessel flow rate.

For steady state experiment, it could provide data of the artificial steady state condition. Although the decay heat is continuously changes along the time in actual accident scenario, the steady state experiment could provide a brief guideline for the performance of the RVACS. 1.0 % and 1.2 % of the decay heat was planned to be tested in the experiments. Flow rate of the external air was fixed as approximately 44.5m^3/h, which corresponds to the maximum flow rate of the RVACS in the Choi’s analysis.

Regard to the transient experiments, design and operation range of the SINCRO-IT which could secure similarity should be considered. The facility designed to has similarity under natural circulation, therefore, only natural circulation was considered. However, among the design-basis accidents, there is no accident scenario under only natural circulation. Therefore, an arbitrary re-criticality after shutdown was assumed for our test condition. Sudden increase of power by re-criticality from 1 to 2 % of the power was assumed. Flow rate of the external air was fixed as 44.5m^3/h. which was same to that of the steady state experiments.

Test matrix was summarized like Table II. Re-criticality was assumed as sudden increase of power like step function.

Table II: Test matrix

Condition	**Power**	**Flow rate**	**Notes**
Steady	1.0 %	44.5 m^3/h	
	1.2 %	44.5 m^3/h	
Transient	1.0 % → 2.0 %	44.5 m^3/h	Sudden increase from steady state

3. Results and Discussion

3.1. Steady state

Fig. 2 shows temperature distribution of the Wood’s metal pool in the 1 % of the decay heat condition. Pool could be separated as a upper plenum, lower plenum. The upper plenum and lower plenum was separated by a bulkhead in the middle of the left side, which simulates redan in the PGSFR. Temperature stratification was observed all over the pool. The upper part of the pool showed higher temperature than the lower part of the pool in general. Just after heating zone, Wood’s metal was heated up to 81 – 82ºC. Heated Wood’s metal made high temperature zone in the upper plenum, and the maximum temperature was 82.7ºC.

Heated Wood's metal flowed to the cooling boundary, which is at the left side of the figure. The pool showed decreased temperature near the cooling boundary. Cooling boundary temperature was evaluated as 74.4ºC in the experiment. It is natural that the cooling wall temperature showed similar temperature to the pool, rather than air cooling channel. Because heat transfer coefficient of the Wood's metal is much higher than air, temperature difference of the Wood's metal and wall was much lower than that of the wall and the air. There is significant temperature difference between the upper plenum and lower plenum, which are divided by horizontal separator. The fluid was continuously cooled though the cooling wall and moved down to the lower plenum with 82.1ºC of the temperature, which was observed at the hole of the bulkhead. After cooling in the lower plenum, the Wood's metal cooled down to the 78.9ºC, and re-entered to the heating zone. Overcooling and solidification of the Wood's metal was partially observed. Considering melting points of the Wood's metal, 73 – 77ºC, there were solidified regions, three points in the left side of the bottom, and one point in the right side of the bottom. Although it was partially solidified, it did not affect to the overall circulation of the pool, so that effect of the solidification was neglected.

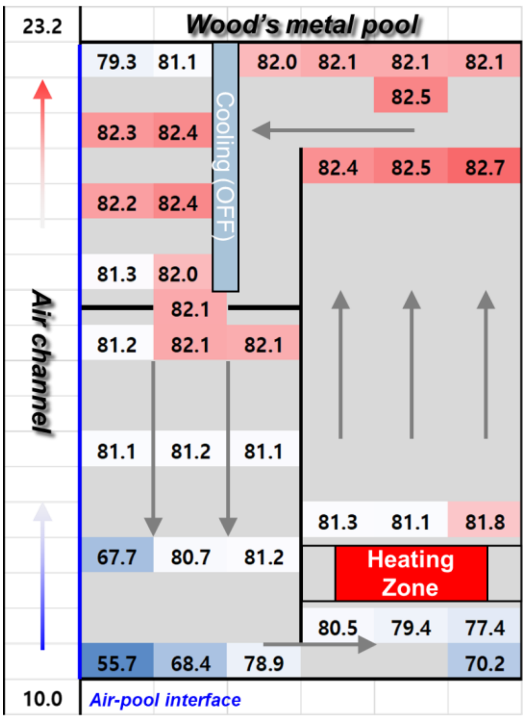

Fig. 2. Temperature distribution – 1.0 % decay heat, steady

During the data interpretation, solidification was not considered. With 1 % of the decay heat, the maximum sodium temperature was 751.5ºC. The RV temperature was evaluated as 733.3ºC, which showed similar temperature with pool.

Temperature distribution characteristics did not change significantly in 1.2 % of the decay heat condition. Only solidification area was decrease. Therefore, results of the steady state and tendency of the main safety parameter (RV temperature, pool maximum temperature) were summarized in Table III. In both conditions, the RV temperature in the prototype was exceeded the RV temperature limit as 650ºC. Regard to the sodium boiling, both conditions showed temperature below 900ºC, which is sodium boiling temperature considering hydraulic static head. Therefore, safety margin for pool boiling is larger than the RV creep, in this arbitrary 2-D reactor.

Table III: Test matrix

Power	T, RV		T, pool, max	
	Exp.	Proto.	Exp.	Proto.
1.0 %	74.4ºC	733.3ºC	82.7ºC	751.3ºC
1.2 %	86.3ºC	864.7ºC	91.1ºC	882.1ºC

3.1. Transient

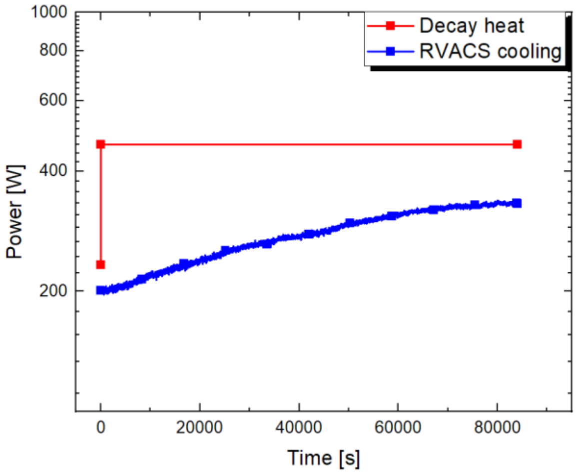

Fig. 3. Heating and cooling during the transient, 1→ 2%

Heating was suddenly increased to simulate the arbitrary re-criticality, while cooling was slowly developed according to the increase of the system temperature. It is summarized in Fig. 3 At the beginning of the experiment, heat was given as approximately 223 W, while heat removal through the RVACS was approximately 200 W, which corresponds to the insulation rate of the facility. At 0 second, approximately 90 % of the heat was removed by the RVACS. After the transient start, heating was increased as twice immediately, however, the development of the RVACS cooling was quite slow. At the end of the experiment, 84,000 seconds, heat removal through the RVACS was only 330 W. Considering 466 W of the heat input, only 71 % of the heat was removed though the RVACS. Considering 90 % of the insulation rate of the facility, cooling of the RVACS was not fully developed after almost 24 hours. Therefore, temperature of the pool was steel increasing until the experiments finished.

Temperature behavior was summarized in Fig. 4, and its translation to the arbitrary 2-D reactor was summarized in Fig. 5. Regard to Fig. 5, data were cut-off after sodium boiling. Temperature increase could be divided into two phases. First phase is melting of the pool. As mentioned in the steady state analysis, there were solidified regions at the bottom corners of the pool. These regions began to melt as temperature rises over melting point of the Wood's metal. That's why there was sudden changed of the slope of the temperature in the lower plenum at approximately 22,000 seconds, and bottom at 50,000 seconds. After melting, overall pool temperature increased linearly, all together.

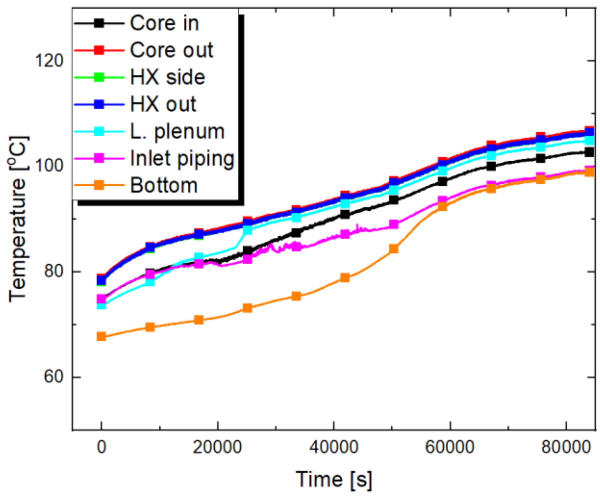

Fig. 4. Temperature behavior during experiment, 1→ 2%

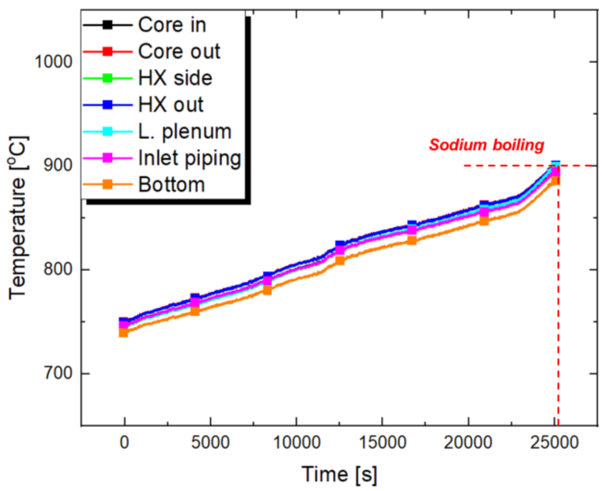

Fig. 5. Temperature behavior of the prototype, 1→ 2%

In the translated data, subtle change of the temperature behavior due to melting was not significant compared to the system temperature behavior. Sodium boiling time and average temperature increase rate were selected as standards for validation of the system code. Sodium boiling was assumed to occur at 900°C, and it was observed after approximately 25,100 seconds after increment of the power. Average temperature increase rate during the experiment was approximately 6°C per 100 seconds. These results would be used for the validation of the system code.

4. Conclusions

SINCRO-IT was designed based on the characteristics of the PGSFR, to conducted integrated and transient experiments for the RVACS. Two different similarity laws were employed, while their time scaling ratios coincidence each other.

Under steady state, sodium boiling was anticipated slightly more than 1.2 % of the decay heat, while RV creep was anticipated less than 1.0%. Safety margin for the RV creep is smaller than that of the sodium boiling.

Regard to transient experiment, 1.0 → 2.0 % sudden power increase was assumed. 6oC per 1,000 seconds of the temperature increase, and sodium boiling 25,100 seconds was evaluated through the simulating experiments. These results would be used for system code validation.

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REFERENCES

[1] 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.

[2] 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, October 24-25, 2019, Goyang, Korea.

[3] K. M. Kim, J. H. Hwang, S. Wongwises, D. W. Jerng, and H. S. Ahn, Design of A scale-down experimental model for SFR reactor vault cooling system performance analyses, Nuclear Engineering and Technology, Vol. 52, pp 1611, 2020.

[4] 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, Transactions of the Korean Nuclear Society Autumn Meeting, October 29-30, 2015, Gyeongju, Korea.

[5] 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.

[6] M. H. Lee, D. W. Jerng, and I. C. Bang, Combination of the different similarity law for transient analysis of the RVACS, Transactions of the Korean Nuclear Society Spring Meeting, May 13-14, 2021, Jeju, Korea.

[7] 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.

[8] 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.