Combination of the different similarity law for transient analysis of the RVACS

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

Safety analysis of the nuclear reactor is conducted by the system code and the reliability of the system code is determined by the physical models employed in the code, and validation against experimental results. The experimental validation of the code includes transient analysis as well as steady state analysis.

For the prototype gen-IV SFR (PGSFR), there are direct heat exchanger (DHX) and reactor vessel auxiliary cooling system (RVACS) for the decay heat removal [1]. For the RVACS, there is no heat exchanger, and the decay heat is removed through the internal sodium natural circulation and the external air natural circulation. To apply RVACS to the system code, it should be validated against experiment. Regard to the experiment, both domains; external air natural circulation and internal sodium natural circulation, should be analyzed. It was revealed that intra- and extra-vessel phenomena could be separated using temperature-based boundary condition under steady state [2]. Therefore, the sodium natural circulation was investigated by Lee, and Kim et al. investigated air natural circulation under steady state [3, 4].

However, safety analysis has intrinsically transient characteristics. Thus, transient experiment is required for the system code validation. Especially, the RVACS has a unique boundary condition. Cooling of the intra-vessel sodium natural circulation is conjugated with heating of the extra-vessel air natural circulation. They interact each other in real time, therefore, transient analysis is much more important for RVACS compared to conventional safety analysis.

To experiment directly with real system, there would be many problems such as economic, safety, and handling problem, for temperature of the system and the reactivity of the sodium. So, it is reasonable to experiment with simulant. Quantitative analysis for the sodium natural circulation with simulant, which could be represented by modified Boussinesq number (Bo') has been validated by Eguchi et al. and Lee et al. [5, 6]. Regard to external air, Ishii scaling method was applied in Kim et al.'s work [4, 7].

Of course, scaling of the parameter in the two different similarity law was different each other in the previous work. However, it should be unified to conduct transient analysis, which includes real time interaction of the boundary condition. To combine intra-vessel and extra-vessel experiment with their own simulant, new methodology to achieve similarity for both intra- and extra-vessel simultaneously.

In this paper, combination and compromise of the two similarity laws for unified transient analysis were analyzed with reference design, whose prototype is the PGSFR, which is shown in Fig. 1. Scaling of the necessary parameter and corresponding similarity, compromise of other parameter, and effect of distortion by the compromised parameter were discussed.

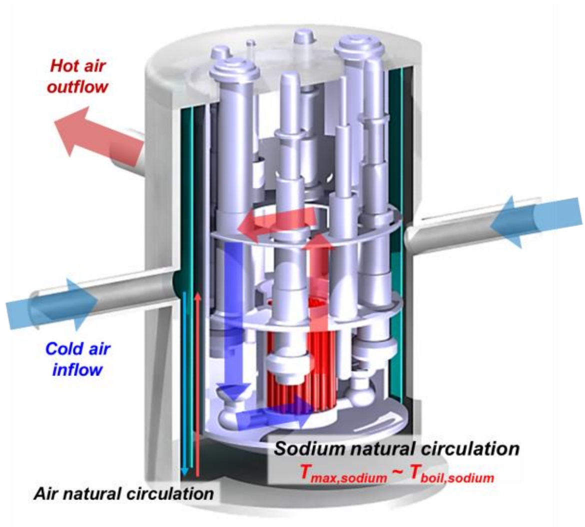

Fig. 1. Schematic of the RVACS in the PGSFR [5]

2. Discussion on the similarity laws

2.1. Bo' based similarity law

The Bo' based similarity law was derived from non-dimensionalization of the governing equation with several assumptions. The system was assumed as 1-D, focusing on the overall heat transfer of the system. Steady state assumption was also introduced, however, it could have reasonable level of similarity for the transient analysis. Richardson number (Ri) was assumed as unity.

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

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

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

Equation (1) and (2) show definition of the important non-dimensional number for the similarity. Because modified Grashof number and Bo' have many parameters in common, it is hard to de-couple these two numbers. Therefore, priority between these two parameters should be defined, and it was revealed that Bo' is more important than Gr' in terms of the similarity of the temperature distribution under natural circulation. It is natural because the Bo' was derived from the non-dimensionalization of the energy equation, and it represents the ratio of heat transfer by natural circulation to conduction. Equation (3) is Euler number (Eu), which is related to pressure drop of each component in the system. Different to Bo' and Gr, it could be independently manipulated by orifice. It could compensate discordance in flow similarity by compromised Gr'.

Therefore, scaling of parameters were adjusted to make identical, or similar Bo'. Eu could be independently satisfied by orifice, and Gr' should be compromised in the similarity law itself.

2.2. Ishii and Kataoka similarity law

Original Ishii's similarity law includes two-phase similarity, however, only single-phase similarity was discussed for air natural circulation.

Similar to Bo' based law, Ishii's law was also derived from non-dimensionalization of the governing equation in the aspect of divided section in the loop. As a result, following non-dimensional numbers were derived.

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

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

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

$$t^*_{0,solid,i} = \left(\frac{\alpha_s L_0}{\delta^2 u_0}\right)_i \tag{7}$$

$$Bi = \left(\frac{h\delta}{k_s}\right)_i \tag{8}$$

$$Q_{s,i} = \left(\frac{q_s''' L_0}{\rho_s c_{p,s} u_0 \Delta T_0}\right)_i \tag{9}$$

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. Other three numbers (solid time ratio number, Biot number, and heat source number) are related to heat transfer in the solid domain, therefore, they were less important than fluid related numbers.

In the aspect of natural circulation of the external air, Ri, St, and friction number were main similarity parameters. Similar to the Bo' base law, the friction number could be changed independently. Therefore, design parameters were determined to make identical Ri and Bo between the prototype and the model.

2.3. Consideration for transient experiment

To observe interaction of intra- and extra-vessel natural circulation, simultaneous experiment was required using simulant. Similar to actual RVACS operation, boundary of one natural circulation is determined by the other natural circulation.

Because two natural circulation experiment were conducted in a one experimental facility sharing boundary, length scale of the two simulating experiment should be identical. In other words, both natural circulation domains were reduced by same length reduction ratio.

Because two natural circulation interact at the boundary in the same time frame (real time), time ratio number should be identical. The agreement of time scale is most important for combined, transient experiment. If length scale is different each other, one side could change its scaling ratio to make identical ratio compromising similarity. However, if time scale was not the same, meaning of the transient experiment is degraded because the interaction at the boundary is inherently transient phenomena. Therefore, agreement of the time scale is required for transient analysis in prior to other similarities.

3. Conceptual design of the experimental facility

3.1. Time ratio scaling

$$t_0 = L_0 / u_0 \tag{10}$$

$$t_{ref,R} = \left(\frac{\rho c_p L_0^4}{\beta g Q}\right)_R^{1/3} \tag{11}$$

$$t_{0,fluid,R} = \left(\frac{\rho c_p d L_0}{2\beta g q''}\right)_R \tag{12}$$

Method for time scaling and corresponding time scaling ratio are shown in equation (10) – (12). Time scale 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 (11) and (12), 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.

3.2. Characteristics of the simulants

For the air simulating experiment, it acts like a cooling jacket for inner pool. Therefore, simulant of the air should have favorable characteristics to make cooling loop. Air and water were considered as candidates for air simulant. Advantages and disadvantages for air and water were summarized in Table I. Time ratio was obtained under isotropic scale reduction with proper heat flux satisfying manufacturability and heat transfer similarity, which could be represented by St in equation (6). Reference heat flux for the sample calculation was assumed as 1 kW/m^2.

Table I. Simulant for ex-vessel air circulation

	Air	**Water**
Advantages	- Always single phase - Relatively lower power	- Small scale - Low overall system temperature
Disadvantages	- Large scale - High overall system temperature	- Boiling issue - Relatively higher power
Time ratio (1/10 scale)	1.71 (@ 0.1 kW/m^2)	1.00 (@ 20 kW/m^2)

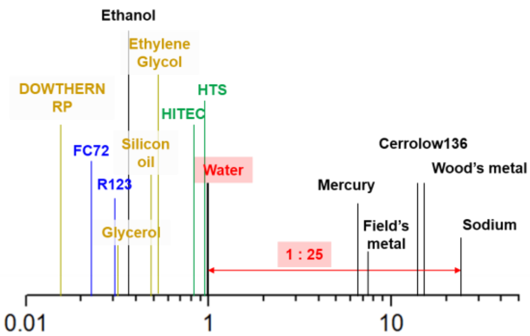

Fig. 2. Relative length scale for the identical Bo' [5]

Both time ratio number of air and water are larger than unity, and it means that relative times in the experiment goes faster than the actual condition. 1 second in the air experiment corresponds to 1.71 seconds in the actual condition. Considering equation (12), although density and specific heat of the water is greater than those of the air, heat flux was 20 times increased for St similarity, time ratio of water became smaller than that of air. In case of water experiment, time ratio approximates to unity, which means time in the experiment is equal to real time.

Regard to the simulant of the sodium, relative length scale for identical Bo' was investigated by Lee et al. assuming water as a standard [5]. According to Fig 2, water has the smallest scale difference to original working fluid sodium, except for other liquid metals. Too much scale reduction could cause distortion in the geometrical and flow similarity. Additionally, water is the most well-known fluid. Therefore, water could be a nice simulant for sodium and it has been proved by many other researches, having scale from 1 : 25 to 1 : 5. As shown in generous range of the scaling, length reduction ratio could be compromised because Bo' still have reasonable degree of similarity in the compromised scale. According to equation (11), although specific of the sodium is smaller than water, considering of the magnitude of the length reduction in the water and 1/3 power in the definition, time ratio number of water was near to unity. Therefore, another simulant for sodium was additionally considered, Wood's metal. Among the possible liquid metals, Wood's metal was selected for various reasons. For economic point of view, the Field's metal and low melting alloys including indium were excluded. And the mercury has strong toxicity. Among lead-based alloys, whose physical properties are similar, Wood's metal was selected for its operation experience. It has higher density and small specific heat capacity, therefore, has similar volumetric heat capacity than sodium. Small volumetric expansion coefficient to temperature is a unique characteristic of the Wood's metal. Therefore, Wood's metal could have large time ratio number than water as a simulant of the sodium.

Table II. Simulant for in-vessel sodium circulation

	Water	**Wood's metal**
Advantages	- Easy to handle	- No boiling
Disadvantages	- Boiling issue	- Solidification issue
Time ratio (1/10 scale)	1.24	0.81

Similar to the external air, for the inner sodium, advantages and disadvantages of the simulant were summarized in table II. Power was automatically reduced proportional to the volume. Time ratio of the Wood's metal is smaller than that of the water because Wood's metal has smaller volumetric thermal expansion coefficient.

Here, time scale change and properties of the simulant should be considered. For simulant of the sodium, time scale is hard to change because it contains 1/3 power. Therefore, it is reasonable to change time ratio of the external side. To change time ratio for given material, height (L), channel width (d) and heat flux (q") could be changed. However, it should satisfy St similarity in equation (6). Therefore, the width should follow the tendency of height scale change. In reduced facility, heat flux should be decreased to compensate length reduction in both directions, height and width. To increase time ratio, heat flux of the experimental facility should be increase because ratio of the heat flux of prototype to model is in the denominator. On the other hand, to decrease time ratio, heat flux of the experimental facility should be decreased. In addition, if length scale is reduced more, time ratio increases.

Using given time ratio in Table I and II, in case of a combination of (water, air) for simulants of sodium and air respectively, time scale of air should be decreased. In this case, heat flux at the air heating boundary is too small to have enough resolution for the data. In case of (water, water), heat flux at the heating boundary should be larger than current value. 20 kWm^2 of the heat flux is excessive amount to be transferred by inner water natural circulation. Therefore, water could not be used as a simulant for the sodium. It is similar to the Wood's metal. Melting point of the Wood's metal is 80°C and boiling point of the water is 100°C. In (Wood's metal, water) combination, large heat flux transferred to the water and inlet temperature of the water should be higher than 80°C to prevent solidification of the Wood's metal. At the same time, boiling of the water also prohibited because water simulate single-phase heat transfer of air. Therefore, this combination is fundamentally inappropriate.

The only possible combination of the simulants is (Wood's metal, air) for (original sodium, water), respectively. As shown in Fig. 2, size of the Wood's metal facility could be increase compared to water facility and it could compensate heat flux reduction to match time ratio. It does not make solidification or boiling issue with enough resolution for data. Adjustable parameters were properly manipulated for similarity and important similarity parameters were summarized in Table III. - 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 sill 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 100 times of the differences. Therefore, our ratio as 1 : 10 was reasonable.

Table III. Similarity of transient experimental facility

	Intra-vessel	**Extra-vessel**
Original fluid	Sodium	Air
Simulant	Wood's metal	Air
Length scale	1 : 4	
Time ratio	1 : 0.644	
Heat flux	0.1 kW/m^2	
Expected ΔT	15.6°C	-
Stanton #	-	1 : 1.03
Ri #	1 : 1	1 : 1
Bo' #	1 : 0.10	-

4. Conclusions

To design experimental facility for transient experiment of the RVACS, combination of the simulant and proper scaling were suggested with multiple domain and multiple similarity law. For the suggest combination of the simulant, (Wood's metal, air) as simulant of (sodium, water) respectively, main similarity parameters for each domain (Bo' and St) were reasonably satisfied. Common parameters like length scale, time ratio, and heat flux were also obtained to unite two different similarity law in the one experimental facility. The experimental facility would be designed in detail for further work.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Energy Research Program through the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT) (2020M2A8A4022882).

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, Simulating Sodium Pool Natural Circulation in RVACS Operation Using CFD, Transactions of the International Congress on Advances in Nuclear Power Plants, April 8-11, 2018, Charlotte, NC.
[3] 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.
[4] 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.
[5] 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.
[6] Y. Eguchi, H. Takeda, T. Koga, N. Tanaka, K. Yamamoto, Quantitative prediction of natural circulation in an LMFR with a similarity law and a water test, Nuclear Engineering and Design, Vol. 178, p.295, 1997.
[7] 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.