Design of the experimental facility for the RVACS natural circulation of the PGSFR, SINCRO-3D

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1. Introduction

To achieve the passiveness for the decay heat removal system of the liquid metal cooled fast reactors (LMRs), the natural circulation is the only one heat transfer mechanism. Unlike general pressurized water reactor, phase change cooled not be allowed for the LMRs. There are two main type of the LMRs; one is the sodium-cooled fast reactor (SFR) and the other is lead-cooled fast reactor (LFR). In case of the SFR, boiling of the sodium causes insertion of the positive reactivity by the positive void coefficient. Additionally, in terms of the material integrity, sodium boiling temperature is sufficiently high for the structural materials to be degraded or undergo creep failure. In case of the LFR, the boiling point of the lead is much higher than the melting point of the structural material. Thus, the decay heat removal by the phase change hear transfer is impossible in the LMRs and the natural circulation is the only heat transfer mechanism.

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]. The DHX is heat exchanger immersed in the reactor pool. 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. For the DHXs, because it could be adopted to the loop-type reactors, many researchers already investigated for the natural circulation phenomena. Takeda et al. conducted an experiment for the sodium natural circulation in the 1/20 reduced slab model water facility [2]. Effect of the decay heat level was observed at the various point of the pool and the experimental results were compared to the numerical results. To observe a fundamental three-dimensional effect like asymmetric heat removal, the experiments were conducted in the AQUARIUS facility [3]. For the three-dimensional phenomena, the RAMONA and the NEPTUN facility were developed and effect of the scaling ratio and exact temperature distribution in the pool were observed [4-7].

However, different to the DHXs, whose heat removal could be treated as the heat sink at the heat exchanger region, the heat removal of the RVACS is achieved at the reactor vessel (RV) wall. It means that the heat removal of the RVACS could not be simplified as volumetric heat sink like that of the DHXs. The heat sink term in the RVACS should be treated as heat flux distribution at the RV wall and its natural circulation phenomena itself is also important for the temperature distribution inside of the pool. Under the RVACS operation condition, the sodium is heated from the core and rises to the upper plenum. Then, it is slightly cooled by the narrow gap between the redan and intermediate heat exchanger (IHX), and goes downward through the IHX. Then, the sodium is re-entered to the core through the pump and corresponding piping. It has the almost same flow with the normal operation, however, the driving force of the RVACS is natural circulation. As written, the flow structure of the natural circulation under the RVACS operation is inherently three-dimensional. In the upper plenum, the IHXs are not arranged in the equally spaced circular position. Corresponding redan is also shape like bow tie. For the lower plenum, the IHXs and pumps are not in the same axial position. Therefore, the natural circulation flow through theses structures should have three dimensional characteristics.

However, for the reactor pool natural circulation, there has been no proper experimental facility. By Lee et al., SINCRO-2D experiment was conducted and effect of decay heat level and external air-cooling condition was experimentally researched [8]. To expand research scope to the three-dimensional phenomena, the facility named simulating natural circulation of the reactor pool under the RVACS operation condition – 3-dimensional (SINCRO-3D) was designed based on the similarity law. In this article, the similarity law, design principle, and specification of the SINCRO-3D facility would be discussed.

2. Similarity law

The objective of the SINCRO-3D facility is to observe the temperature distribution of the reactor pool under the RVACS operation condition. For the simulation of the temperature distribution in the system, the modified Boussinesq number (Bo’) based similarity law is a good choice. Most of the previous research also based on the Bo’ based similarity law [2-8]. In this section, the concept and derivation process of the Bo’ based similarity law were summarized.

2.1. Non-dimensionalization of the governing equations

There are three governing equations for the natural circulation phenomena: the mass, momentum and energy conservation equations. Important non-dimensional numbers could be derived from the non-dimensionalization of the governing equations.

To non-dimensionalize the governing equations, reference for each parameter were required. For the natural circulation, in the system point of view, there is only reference for the length scale. In other words, for the temperature difference, velocity, and time, there is no clear reference. These parameters could be expressed using system properties. From the balance between the buoyancy potential energy and kinetic energy of the natural circulation, and from the balance between the heating rate and cooling by convection, reference parameters for the temperature difference, velocity and time could be derived like equation (1) – (3).

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

$$u_{ref} = \left(\frac{\beta g}{\rho c_p L}\right)^{1/3} Q^{1/3} \quad (2)$$

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

The three governing equations could be non-dimensionalized by using these three reference parameters. The non-dimensionalized three governing equations are summarized in equation (4) – (6). Here, the heat source term and the heat sink term were represented as the volumetric heat generation and heat flux cooling, respectively. Characteristics of the RVACS are reflected into these two terms. In the reactors, heat is generated in the core region, and it is modeled as the volumetric heat generation term in equation (5). Other research for the DHX operation condition used the same heat generation term [2]. The distinguished point of the RVACS is heat sink term represented as heat flux in equation (5). Considering cooling through the RV wall, it is obvious that the heat sink term could not be simplified as the volumetric heat sink term in the DHX approaches. Temperature change of the working fluid through the RV wall could be expressed as cooling heat flux/ Therefore, the author employed the heat flux term to reflect operation characteristics of the RVACS.

$$\frac{\partial u_i *}{\partial x_i *} = 0 \quad (4)$$

$$\frac{\partial u_i *}{\partial t *} + u_j * \frac{\partial u_i *}{\partial x_j *} = \frac{1}{Gr'^{1/2}} \frac{\partial^2 u_i *}{\partial x_j^2 *} - \frac{\beta g \Delta T_{ref} L}{u_{ref}^2} T * \delta_{i3} - \frac{\Delta P}{\rho u_0^2} \frac{\partial P *}{\partial x_i *} \quad (5)$$

$$\frac{\partial T *}{\partial t *} + u_j * \frac{\partial T *}{\partial x_j *} = \frac{1}{Bo'^{1/2}} \frac{\partial^2 T *}{\partial x_j^2 *} + \frac{Q_0 L}{\rho c_p u_{ref} \Delta T_{ref}} - \frac{Q''}{\rho c_p u_{ref} \Delta T_{ref}} \quad (6)$$

Here, two important non-dimensional numbers were derived from the diffusion terms on the right-hand side of equations (5) and (6): the modified Grashof number (Gr') and the Bo'. Their definitions are given in equations (7) and (8), respectively.

$$Gr' = \left(\frac{\beta g}{\rho c_p}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\nu^2} \quad (7)$$

$$Bo' = \left(\frac{\beta g}{\rho c_p}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\alpha^2} \quad (8)$$

Except for the Gr' and Bo', there are more important parameters for the similarity. For the momentum conservation equation, term related to buoyancy potential energy could be treated as unity because it was already assumed as unity during the derivation of the reference parameters. For the pressure drop, the pressure drop coefficient is more important than the Gr' according to the order of magnitude. The order of magnitude of the pressure drop coefficient is larger than that of the Gr'. Therefore, for the overall flow similarity, the pressure drop coefficient is more important than the Gr', while the Gr' is related to the flow regime.

For the energy conservation equation, the parameter related to the heat source term could be treated as unity by substituting references by its definition in equation (1) – (3). Regard to the heat sink term, the situation is quite similar. However, here, we should consider about the distribution of the cooling heat flux through the RV wall. It could be represented by the cooling wall temperature, which is related to the heat flux distribution through the wall.

In summary, there are three important numbers for the natural circulation similarity: the Bo', the pressure drop coefficient, and the Gr'. Among these numbers, because we focus on the similarity of the temperature distribution, the Bo' is the most important.

2.2. Simulant for the sodium

The Bo' is the most important numbers for the similarity of the natural circulation. In fact, Bo' could be changed by the changing the volumetric heat generation rate, length scale, and working fluid, volumetric heat generation was fixed for the convenience of the experiment. Therefore, for the identical Bo' relationship between the working fluid and length ratio could be represented as figure 1.

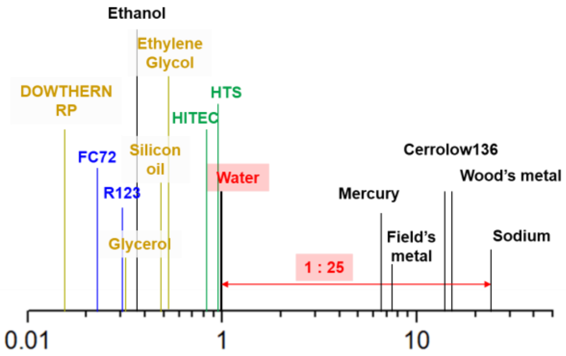

Fig. 1. Relative length scale for the identical Bo'

According to figure 1, water has the smallest scale difference to original working fluid sodium. Too much scale reduction could cause distortion in the geometrical and flow similarity. Additionally, water is the most well-known fluid. Therefore, simulant for the sodium was determined as water. Corresponding scale reduction ratio is 1 : 25, however, it was reduced more and it would be discussed in the following session.

3. Design of the SINCRO-3D

As shown in the exact scale for the relative length scale was 1 : 25. However, to obtain similarity in the aspect of the flow regime and geometry, it was scaled-up to the 1 : 10. In this scale, the Bo' was compromised with other parameters, however, the logic for the scaling-up could be explained by the preliminary CFD analysis. Figure 2 shows the normalized temperature at several points of the SINCRO-2D, which was designed by Lee et al. [8]. By these results it could be justified that scaling up is not severely distort the temperature field and brought about many advantages in terms of the flow and geometry.

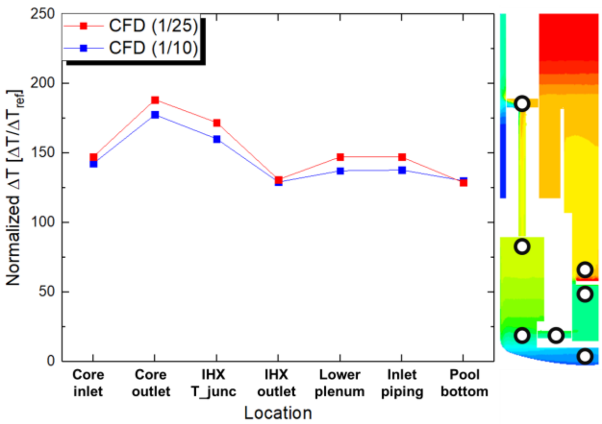

Fig. 2. Distortion of the temperature by scaling up

The objective of the SINCRO-3D facility is to observe the temperature distribution of the reactor pool under the RVACS, and the PGSFR is the prototype of the SINCRO-3D. Therefore, the design of the SINCRO-3D is based on the related structures with RVACS in the PGSFR. Under the natural convection, the flow is generated through the inlet plenum, core, upper plenum, IHX, lower plenum, pump and inlet piping of the PGSFR. Relative contribution to the pressure drop of each part is summarized in table I.

Table. I: Relative pressure drop of each part [9]

Component	Pressure drop	Contribution
Inlet plenum	0 kPa	0 %
Core	6.4 kPa	79.0 %
Upper plenum	-0.4 kPa	-4.94 %
IHX	0.4 kPa	4.94 %
Lower plenum	0.6 kPa	7.41 %
Inlet piping	1.1 kPa	13.6 %
Total	8.1 kPa	100.0 %

By the order of magnitude analysis, importance of the matching pressure drop coefficient was recognized. As shown in table I, under natural circulation, pressure drop was mainly contributed from the core and inlet piping. In addition to the core and inlet piping, the IHX would be additionally considered for similarity because it has specified and confined geometry. In case of the upper and lower plenum, pressure drop was hard to be considered because of the unclearness during specified pressure drop analysis. Therefore, three components were considered for the similarity of the pressure drop: the core, IHX, and inlet plenum.

Pressure drop coefficient was obtained by numerical methods. ANSYS-CFX was used for the analysis and three components were considered: the core, IHX, and inlet plenum. The flowrate was determined as same with the reference [9], 10% of the normal operation. For the calculation of the pressure drop coefficient, the velocity was used as reference velocity of each system, like equation (9). The results were summarized in the table II.

$$\xi = \frac{2\Delta P}{\rho u_{ref,system}^{2}} \qquad (9)$$

Table II. Similarity of the pressure drop coefficient

Component	Pressure drop coefficient		Difference
	PGSFR	SINCRO-3D	
IHX	46.34	47.87	+ 3.3%
Inlet piping	133.76	133.11	- 0.5 %
Core	748.13	737.20	- 1.5 %

For the target components, pressure drop of the components showed good accordance with that of the prototype reactor. In case of the IHX, the number of the grid spacer in the shell was reduced from 5 to 2 to make identical pressure drop coefficient because most of the pressure drop was generated from the grid spacers. Other dimensions were determined based on the 1/10 linear scale reduction because the isotropic scaling was assumed in the Bo' based similarity law. Regard to the pump and the inlet piping, the size of the downward piping was modified. The impeller of the pump would be manufactured by 3-D printer because of its complex geometry. Core was represented as summation of the fuel assembly. All components in the actual fuel assembly were reflected into the design of the heater assembly in the SINCRO-3D. However, the contribution of each component in the assembly for pressure drop was different. For the actual fuel assembly, pressure drop was mainly generated in the fuel rod region, while main pressure drop was generated by the inlet receptacle and outlet handling socket. Nevertheless, total pressure drop in the aspect of the overall assembly showed good accordance with that of the prototype. Final 3-D image of the SINCRO-3D was illustrated in figure 3. Main parts for the natural circulation: the IHXs, fuel assemblies, and pump and inlet piping are represented in the figure 3 as orange, red, and green color, respectively. The DHXs are represented by the blue and the structures like redan, core shroud and the RV are represented in the yellow.

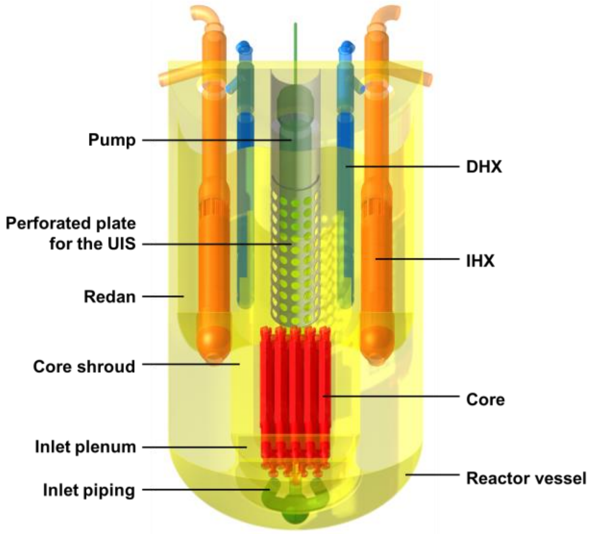

Fig. 3. Schematic of the SINCRO-3D

4. Conclusions

SINCRO-3D, which is the scaled PGSFR for the RVACS natural circulation experiment, has been designed. The water was the simulant for the sodium. Main similarity parameter was Bo' and corresponding reduction scale for the identical Bo' was 1 : 25, however, it was scaled-up to 1 : 10 for the better similarity in the aspect of the flow and geometry. Target components for the identical pressure drop coefficient were IHX, core, and inlet piping, and they showed good accordance with the prototype reactor, PGSFR.

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