Characteristics of the natural circulation of the pool under RVACS condition in pool-type LMR using 2-D slab experiment

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1. Introduction

Reactor vessel auxiliary cooling system (RVACS) is one of the best options of decay heat removal system for the pool-type liquid metal-cooled reactor because of its passiveness and robustness [1]. RVACS not only can remove decay heat but also provide negative reactivity feedback for the mitigation of the accident [2, 3]. Under RVACS operation, decay heat from the core is transferred to the reactor vessel (RV) by natural circulation. Containment vessel (CV) surrounding RV is heated by the heat from the RV and finally dissipate its heat to the external air, which is governed by another natural circulation. Here, internal pool natural circulation and external air natural circulation interact each other because boundary condition of the one side is influenced by the result of the other side. This conjugated heat transfer can be separately studied with proper boundary condition.

It is important to analyze natural circulation inside pool because coolant temperature and structural temperature are mainly affected by the natural circulation. For the experimental approach, coolant of liquid metal-cooled reactor, such as sodium and lead, has a lot of difficulties because of its handling and toxicity. To substitute working fluid, Ieda et al. considered various non-dimensional numbers and corresponding simulant and scale [4]. They concluded that Richardson number, Peclet number, and Reynolds number were important in the aspect of thermohydraulic phenomena. Takeda et al. derived modified Boussinesq number (Bo') and modified Grashof number (Gr'), which were corresponding to the Peclet number and Reynolds number in the forced convection, respectively [5]. They insisted that Bo' is more important than Gr'. Wienberg et al. validated importance of the Bo' by two experimental facilities with different scale and CFD [1]. In steady state, Lee et al. experimentally validated Bo' based similarity law [6]. Eguchi et al. analyzed transient natural circulation and showed that Bo' based similarity law could be extended to the transient condition [7]. Facility named PHESANT was also developed based on Bo' and natural circulation under decay heat removal system was analyzed with PIV [8].

In this study, the focus was on the natural circulation inside the pool and its result, which corresponds to the boundary condition for the external air. Natural circulation in the pool was analyzed based on the specification of the RVACS in prototype gen-IV sodium-cooled fast reactor (PGSFR).

2. Experimental methods

2.1. Scaling analysis

It has been experimentally validated that natural circulation behavior, especially temperature distribution, could be characterized by Bo' [6]. Reference temperature difference (reference ΔT) means representative magnitude of the temperature difference in the system. Bo' and reference ΔT were described in the equation (1) and (2).

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

$$\Delta T = \left(\beta g \rho^2 c^2 L^5\right)^{-1/3} Q^{2/3} \tag{2}$$

Bo' represents ratio between heat transfer by natural circulation to heat transfer by conduction, which is corresponding to the Peclet number in the forced convection. Temperature field could be modified as temperature difference with the lowest temperature point and it can be also expressed using reference ΔT like equation (3). θ means normalized temperature difference. By matching Bo', characteristics of the temperature field can be reproduced, in other words, θ could be reproduced in the experiment.

$$\Delta T = \Delta T_{reference} \times \theta \tag{3}$$

$$\Delta T_{plant} = \frac{\Delta T_{reference,\,plant}}{\Delta T_{reference,experiment}} \times \Delta T_{experiment} \tag{4}$$

As previous mentioned, normalized temperature could be simulated by matching Bo'. Therefore, temperature field in the actual plant could be predicted by experimental data and reference ΔT in the experimental apparatus and the actual plant. It is summarized in the equation (4)

2.2. Experimental design

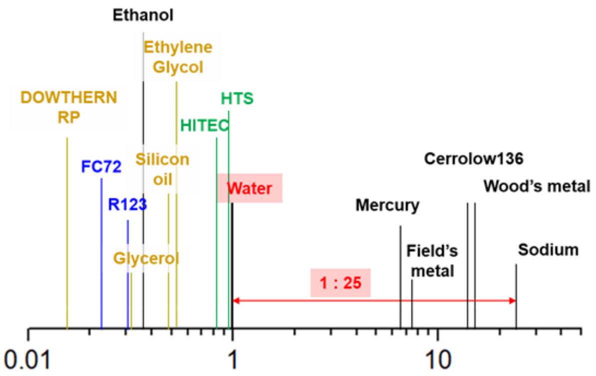

Fig. 1. Relative length scale for identical Bo'

As considered in various previous researches, water was the best simulant for the liquid metal. The other fluids like oil, refrigerant, and molten salt require excessively small scale for identical Bo'. Therefore, water is the best simulant for the liquid metal natural circulation not only for scaling ratio but also its advantages in handling. Length scale ratio between original coolant sodium and water was 1/25 and it is presented in the fig. 1.

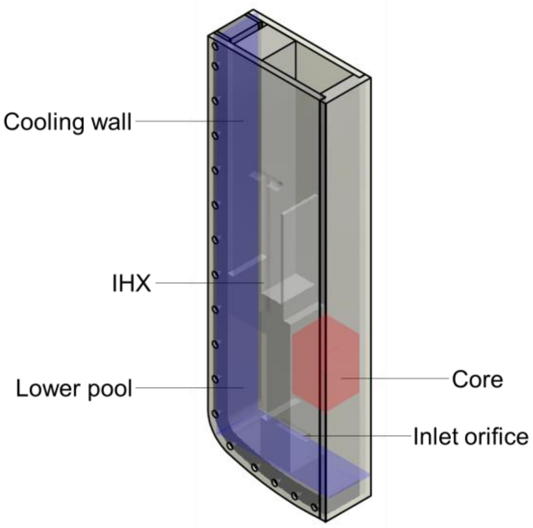

Fig. 2. Schematic of the SINCRO-2D facility

Experimental facility was named as SINCRO-2D, which is abbreviation of the simulating natural circulation of reactor pool in RVACS operation - 2D. As illustrated in the fig. 2, it was designed in two-dimensional slab model. Natural circulation path in the PGSFR, which includes intermediate heat exchanger (IHX), was reflected in the SINCRO-2D. Flow resistance of the inlet piping and pump was modeled as equivalent inlet orifice in the inlet plenum.

Table. 1. Specification of SINCRO-2D

Parameter	PGSFR	SINCRO-2D	Ratio
Radius	4.3 m	173 mm	1/25
Height	15.3 m	540 mm	1/25
Power density	$213.4\ \mathrm{W/cm^3}$		1
ΔT_{ref}	1.528℃	0.248℃	0.162
Bo'	0.86×10^8	1.07×10^8	1/1.25

Compared to reference reactor PGSFR, SINCRO-2D was linearly scaled-down to 1/25 scale. Power density at the full power was the same as 213.4 W/cm^3 and decay heat was calculated based on the power density. In that scale, reference temperature was about 6.2 time smaller in the SINCRO-2D. In other words, magnitude of the temperature field is 6.2 times smaller in case of SINCRO-2D than that of PGSFR. The most important similarity parameter Bo', was almost identical, about 1 x 10^8.

Test was conducted in the 1% of the decay heat condition, which was 3.92 MW and 200 W in the PGSFR and SINCRO-2D, respectively. Boundary condition was assumed as constant temperature because of flattening effect of the radiation between the CV and the RV.

3. Results and Discussions

Temperature profile at the 1% decay heat condition was presented in the figure 3. Water was heated at the heating zone by cartridge heater and cooled down at the left boundary of the pool, which represents the RV of PGSFR. Following the natural circulation path, hot region was generated after the heating zone to the inlet of the IHX. Hot fluid from the core and cooled-down fluid from the narrow gap between the IHX and boundary were mixed at the IHX. This mixed flow came down to the lower plenum. The flow was continuously cooled-down in the lower plenum and re-entered to the core through inlet orifice. Bottom part of the pool, which was located below the core region, did not participated in the natural circulation so that thermocouple at the bottom part of the pool showed distant value from the other part.

Here, two interesting phenomena were observed. First one was natural circulation in the narrow gap. Narrow gap means the narrow pool between the IHX and RV in the hot pool. As shown in the fig. 3, temperature was stratified in the narrow gap. The width of the narrow gap is about 25 cm in the PGSFR, and it was scaled-down to 1 cm in SINCRO-2D. It was thought that the pool was narrow enough to transfer its heat by conduction. However, in the experiment, there was strong evidence of natural circulation in the narrow gap. If we assumed that the heat transferred by only conduction, it could be calculated based on the 1-D

Fourier's law. In this regard, only 0.06 W of the heat could be transferred through the gap under the given geometry and properties of the water. It was negligible value to make such temperature change before and after the IHX compared with current power, 200 W. Therefore, it could be inferred that natural circulation was dominant heat transfer mechanism in the narrow gap despite of its small size. Here, bottom part of the narrow gap did not participate natural circulation and it could be recognized by the temperature data from the lowest thermocouple. Temperature did not change significantly below the third thermocouple in the narrow gap. So that the bottom part of the narrow gap was not influenced by the natural circulation.

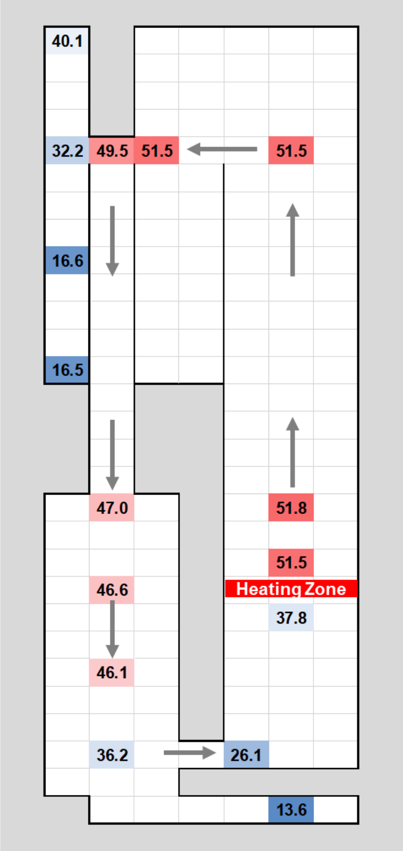

Fig. 3. Temperature distribution in 1% decay heat

Second one was cooling fraction of the RV. In the preliminary research without internal structure such as IHX and inlet orifice, cooling was mainly achieved by the upper part of the RV, where high temperature fluid contact with the RV. However, in the present study with complex internal structures, most of the cooling was achieved in the lower plenum. It could be recognized by the temperature change through the natural circulation path and the temperature change along the flow path was summarized in the table 2. Working fluid was heated up to 51.5℃ at the core outlet and cooled down to 26.1℃ at the inlet piping. Temperature at the outlet of the IHX was 47.0℃. Only 4.5℃ of the temperature decreased through the IHX and about 20.9℃ of the temperature decreased after lower plenum. Therefore, the natural circulation flow was mainly cooled in the lower plenum. It means that heat flux from the RV to the CV was higher in the lower part of the RV. Finally, it could affect heat flux distribution from the CV to the air, which is conjugated with radiation heat transfer to the RV.

Table. 2. Temperature of the flow path

Location	Temperature
Core outlet	51.5℃
IHX outlet	47.0℃
Inlet piping	26.1℃

The maximum temperature difference between the boundary and bulk sodium could be calculated from the equation (4). Temperature difference between the boundary and the hot spot was 38.0℃ in the experiment and it could be interpreted to the that between the RV and hot bulk sodium as 234.1℃. Considering temperature limit of the sodium boiling 880℃, it could be inferred that sodium bulk boiling will not occur until the RV temperature exceed 646℃.

4. Conclusions & Further works

Experimental study about the natural circulation in the coolant pool under RVACS operation was conducted in the SINCRO-2D facility. Hot region was generated after the heating zone to the inlet of the IHX. There was some region where natural circulation flow did not influence, in the bottom of the narrow gap and the pool. As observed in the temperature change through each part, air cooling was achieved in the lower plenum. Despite of the small size of the narrow gap, natural circulation was also dominant heat transfer mechanism in the narrow gap.

The limitation of the present study is temperature of the sodium was evaluated as bulk temperature. To obtain the hottest pool temperature at the thermal boundary layer of the fuel pin, local heat transfer experiment should be conducted.

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