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Preliminary experiment for simulating natural circulation of liquid metal by water

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1. Introduction

In Korea, prototype gen-IV sodium-cooled fast reactor (PGSFR) is under development because sodium is a promising candidate for coolant of the fast reactor due to its superior heat transfer performance and neutronic characteristics. Unlike water, sodium is an unfamiliar liquid for the engineering aspect. To assure the safety of the system using sodium for a working fluid, performance validation of sodium should be conducted and experimentally validated.

Performance evaluation with sodium should be able to cover abnormal and even accident condition. Considering heat transfer mode, it can be divided into forced convection and natural convection. In case of the station black out (SBO), all pumps become unavailable by losing its power and natural convection of the sodium becomes dominant heat transfer mechanism. Only passive safety systems, which do not require external power for their operation, can operate such kind of situation and most of them employ natural convection or circulation, like reactor vessel auxiliary cooling system (RVACS) in PGSFR or RRB in the ASTRID.

Natural circulation of the sodium was experimentally studied in the EBR-II [1,2]. Reactor could be shutdown without scram and decay heat was successfully removed from the core. Hot sodium from the core was cooled at the intermediate heat exchanger (IHX). After experiments in the EBR-II, most of the experiments were conducted as similarity experiment using water. In the decay heat removal system (DHRS) operation condition, natural circulation of the sodium was experimentally studied [3,4]. Tanaka et al. just showed the temperature distribution under wrong scaling with water [6] and Eguchi et al. proved the similarity law under IHX-driven decay heat removal case [7]. Although most of the current experiments related to sodium natural circulation are based on the similarity law, there have been insufficient validation cases for similarity law itself. Tanaka et al. just showed the temperature distribution under wrong scaling with water [6] and Eguchi et al. proved the similarity law under IHX-driven decay heat removal case [7]. RVACS operates under different boundary condition which is cooling from the reactor vessel wall and natural circulation similarity law is still unclearly proven by experiment.

To validate natural circulation similarity law under various condition, series of experimental apparatus named SINCRO-V (SImulating Natural Circulation of Sodium pool in Rvacs Operation – Validation of similarity law) has been developed in UNIST. Before liquid metal experiment, preliminary experiment was conducted for facility operation test to get a physical insight of the natural circulation in the SINCRO-V. Wall heat flux and maximum temperature difference at the steady state were obtained and result of the liquid metal experiment was predicted based on the current result.

2. Experimental methods

Originally, the series of SINCRO-V experiment were designed to operate under water cooling boundary condition. To show similarity of the natural circulation in the liquid metal and the other fluid, Wood’s metal was selected as representing material for liquid metal and water was selected for non-liquid metal fluid. Similarity issue like scaling or simulating material was discussed in the section 2.1 and test condition was described in the section 2.2.

2.1 Similarity issue

Thermal-hydraulic characteristics in liquid metal natural circulation have been suggested and confirmed by scale-down experiments of DHRS [3-6]. Three conservation equations for mass, momentum, and energy for natural circulation are like below.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \nu \frac{\partial^2 u_i}{\partial x_j^2} - \beta \Delta T g \delta - \frac{1}{\rho}\frac{\partial P}{\partial x_i} \tag{2}$$

$$\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x_j} = \alpha \frac{\partial^2 T}{\partial x_j^2} + \frac{Q_0}{\rho c_p} \tag{3}$$

Non-dimensional numbers are derived from normalizing of governing equations and it represent balance between phenomena. Like usual case, such as forced convection or external flow, length scale can be represented as characteristic length. However, in case of velocity, time, temperature, and pressure cannot be represented by given value. Therefore, these values will be derived from the characteristic of the natural circulation.

Flow is driven by buoyancy in natural circulation. From the force balance between buoyant potential energy and kinetic energy of the buoyancy driven flow, reference velocity can be expressed by relationship with other undefined parameters like temperature difference. Reference velocity means representative velocity derived by force balance of governing phenomena. Lefthand side of the equation (4) means buoyant potential energy which was induced by the Boussinesq approximation and definition of the potential energy. And righthand side of the equation (4) means kinetic energy. Comparing the magnitude of the both side of the equation (4), velocity can be driven as equation (5) by means of order of magnitude.

$$\rho g\beta \Delta TL = \frac{1}{2}\rho u_0^2 \quad (4)$$

$$u_0 \sim \left(g\beta\Delta TL\right)^{1/2} \quad (5)$$

Volumetric heating rate can be expressed in reference velocity and temperature difference. From the balance between heating rate, which is on the righthand side of the equation (6), and heat loss by the convection, which is on the left-hand side of the equation (6), heat input can be expressed like (7) as a form of another order of magnitude.

$$u_0 \frac{\partial T}{\partial x} \sim \frac{Q_0}{\rho c} \quad (6)$$

$$Q = Q_0 L^3 \sim \rho c u_0 \Delta T L^2 \quad (7)$$

Reference velocity can be derived by aligning equation (5) and (7) for u0. Similarly, Reference temperature can be derived by aligning equation (5) and (7) for ΔT. Reference time scale is derived from the relationship between reference velocity and characteristic length. These reference properties are summarized in equation (8), (9), and (10) in series.

$$u_0 = \left(\frac{\beta g}{\rho c L}\right)^{1/3} Q^{1/3} \quad (8)$$

$$\Delta T = \left(\beta g \rho^2 c^2 L^5\right)^{-1/3} Q^{2/3} \quad (9)$$

$$t_0 = \left(\frac{\rho c L^4}{\beta g}\right)^{1/3} Q^{-1/3} \quad (10)$$

Finally, using these reference properties and characteristic length, normalizing of the governing equation was conducted to obtain non-dimensional number. Modified Grashof number for velocity distribution and modified Boussinesq number for temperature distribution can be derived as following equations (11) and (12).

$$Gr' = \left(\frac{\beta g}{\rho c}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\nu^2} \quad (11)$$

$$Bo' = \left(\frac{\beta g}{\rho c}\right)^{2/3} \frac{L^{4/3} Q^{2/3}}{\alpha^2} \quad (12)$$

Modified Boussinesq number represents ratio between heat transfer by natural circulation and by conduction, which is similar to Peclet number. Modified Grashof number means ratio between inertial force by buoyancy and viscous force, which is similar to Reynolds number. And for flow similarity, Richardson number and Euler number should be considered together.

Rayleigh number indicates the intensity of natural circulation and it determines heat transfer characteristics. However, the object of these experiment is to evaluate the temperature profile and estimate peak temperature of sodium coolant. Therefore, rather than traditional natural convection approach analyzing heat transfer coefficient at the boundary, reproducing temperature distribution is much more important. And for this kind of temperature profile, modified Boussinesq number is more appropriate than Rayleigh number.

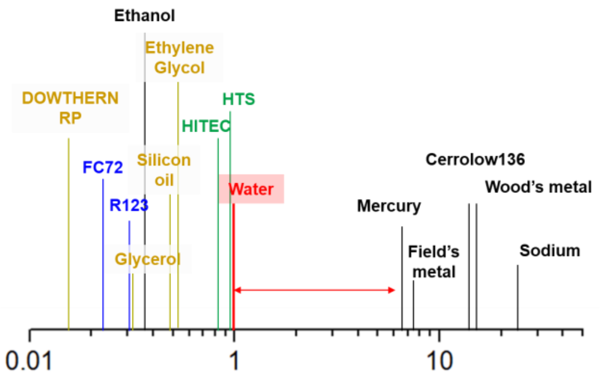

Fig. 1. Relative length scale to have identical modified Boussinesq number

Figure 1 represents various materials' relative length scale. On the right side of the scale, there are various liquid metals. The other fluids including water are located on the left side of the scale. To minimize distortion by scale, it is good to minimize difference of the length scale between two fluid. Among the liquid metals, mercury has the smallest difference of the length scale with non-metallic fluid. However, mercury has toxicity to human and environment. Field's metal was also excluded for economical issue. Between Cerrolow136 and Wood's metal, which have similar magnitude of the length scale, Wood's metal was selected because of previous operation experience. For the simulant of liquid metal, water was the best solution. It can minimize scale difference with liquid metal and the other fluid, and it is also the most familiar and compatible material. Other oils, refrigerants, and heat transfer salts showed smaller length scale to get identical modified Boussinesq number. Finally, the length scale difference between Wood's metal and water is 14.1 : 1.

2.2 Experimental description

To catch overall behavior of the natural circulation, geometry was simplified. Original PGSFR has rectangular-like, smooth wall cross section, but it was simplified to a quadrant in the SINCRO-V. To separate upward flow and insulate heaters from the outside pool, there is an insulation structure at the outside of the heating zone. Relative size of the core was maintained as ratio of the vessel radius to core radius and ratio of the core height to core radius. Based on the scaling analysis, relative size was determined. This process was summarized in the figure 2.

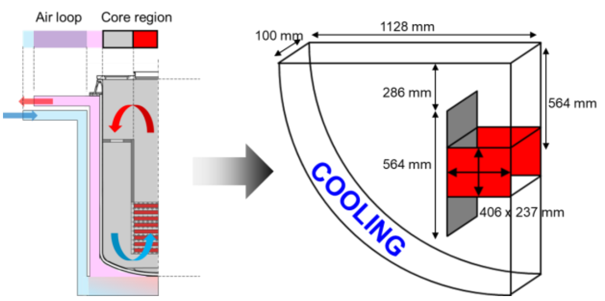

Fig. 2. Schematic of the experimental facility

As discussed in the similarity law, total power was preserved as volumetric heat generation. Power density of the PGSFR is about 2.134MW/m^3 and decay heat is usually assumed as 1 % of the total power. Applying this volumetric heat generation to the heating volume of the SINCRO-V, total power of the SINCRO was about 20kW.

However, to get the single-phase natural circulation with water, water temperature should be below the boiling temperature. According to the result of the insulation test, total thermal resistance between internal pool and ambient was about 0.12^{o}C/W in the atm. About 98.5% of the heat leaked to the cooling side even there was no active cooling but only air. Therefore, to get the single-phase natural circulation, heater power was about 500 W in the current, preliminary analysis with about 25^{o}C of ambient temperature. Test condition and specification of the SINCRO-V were summarized in the table 1.

Table 1. Specification of SINCRO and test power

Parameter	Value
Radius	1128 mm
Length ratio	14.1 larger than water
Weight	450 / 1350 kg
Total power	20 kW
Insulation performance (ambient: atm)	0.12^{o}C/W
Test power (%)	500 W (2.5%)

3. Results & Discussions

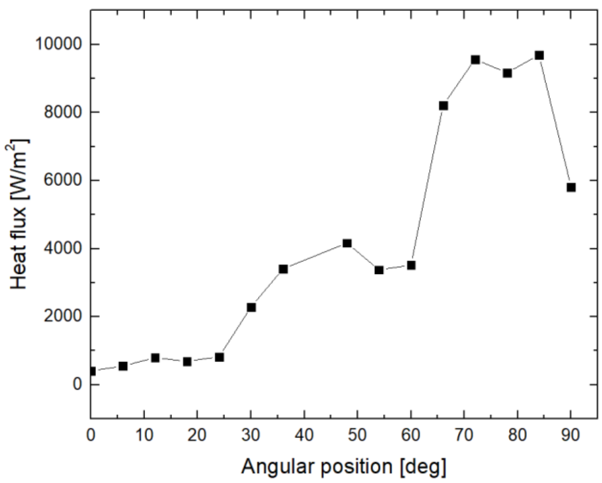

Fig. 3. Heat flux profile at the wall

As calculated in the insulation test, about 98.5% of the heat was removed from the cooling curvature. However, wall heat flux measurement has potential to have a large error. Generally, heat flux was obtained from the Fourier's law and it uses temperature difference between two points, distance, and thermal conductivity of the material. Here, thermal conductivity has the smallest error less than 15 % of the deviation. However, error range of the distance is about 2 mm and it correspond to 25 % of the distance error. It is worse in temperature case. K-type thermocouple has approximately 1.3^{o}C of error in the atm and it corresponds to 25 % of error in minimum and more than 50 % of error in average. Considering 15W/m.K of thermal conductivity of the stainless steel and 8 mm of the distance, this error can make approximately 2500 W/m^2 of the heat flux error. Theoretically, heat flux should be increase as angular position moves upward because natural circulation is more intense in the higher angular position, which is relatively vertical. In case of external surface of lower angular position, natural circulation is less intense in downward face case. However, there were some points showed unexpected behavior, like 54, 60, and 90^o. Considering internal temperature profile in the figure 4, decrease of heat flux at such points could be treated as experimental error.

It is certain that the SINCRO-V was in the steady state, calculated total heat loss from the cooling surface by interpolation of figure 3 was about 670 W and excluding peculiar point, it was about 726 W. Total power level will be increased in the main, liquid metal experiment, so that error related to temperature difference is expected to decrease therefore total error will be decrease.

The maximum temperature of the water pool was 85.131ºC and the minimum temperature was 54.411ºC in the natural circulation flow and about 46ºC in the pool. Pool temperature was estimated using correlation and the heat flux at the position. So that maximum temperature difference is about 30.72ºC, and about 39ºC. These results were graphically summarized in the figure 4.

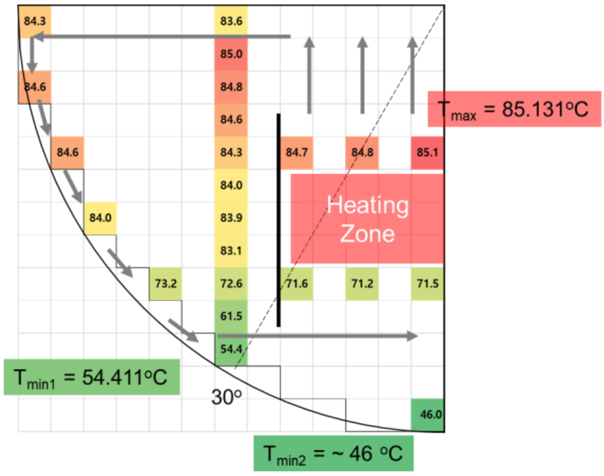

Fig. 4. Summary of temperature profile

The maximum temperature point was observed near the insulating wall. It was the hottest point because it was just after outlet of the heating zone and there was no loss by separator. The minimum temperature point was observed at the end of the downward flow. Combining the pool temperature, wall temperature, and heat flux at the wall, downward flow of the natural circulation was ended at 30-degree position, near the minimum temperature point of the wall. Then, downward flow was separated from the cooling surface and went into the core. In other words, below the 30-degree or below the same height of the separator low end, there was no significant cooling at the cooling surface.

In the preliminary analysis, cooling boundary condition was natural circulation of the air. So that power level should be decreased, and wall temperature distribution was quite uneven. In the main experiment, boundary condition will be modified as water boiling, therefore, more even temperature distribution is anticipated. Bottom part of the quadrant was not well heated in the present experiment because of low thermal conductivity of the water and relatively larger size for water. If Wood's metal is working fluid, and much large power is given, bottom part of the quadrant will be well heated.

4. Conclusion

To validate similarity law of natural circulation, experimental facility named SINCRO-V has been developed. Preliminary experiment was conducted with water to evaluate performance of the facility and get the physical insight of the natural circulation inside of the SINCRO, before the main experiment with liquid metal. Downward flow was separated at the 30-degree region, which was similar height to the separator low end, so that there was no significant cooling at the cooling surface. The maximum temperature was observed as about 85ºC at the outlet of the heating zone and the minimum temperature of the flow was observed as about 54ºC at the downward flow separation point. However, the minimum temperature in the pool was about 46 ºC and it was anticipated to exist the lowest part of the pool.

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