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Effect of Boundary Condition on Natural Circulation in Sodium Pool by RVACS

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1. Introduction

Defense in depth (DID) is key concept of the nuclear safety which has been recently emphasized by Fukushima accident. In-vessel retention through external reactor vessel cooling (IVR-ERVC) was one of the best option for radioactive material keeping inside of the primary circuit pressure boundary. It was adopted in AP 600 and AP 1000 and enhanced safety especially in the point of passive safety.

Similarly, in sodium-cooled fast reactor (SFR), reactor vessel auxiliary cooling system (RVACS) has been developed. RVACS cooling mechanism is like below. Decay heat from the core is transferred to reactor vessel by natural convection inside of the sodium pool. Containment vessel is heated by convection and radiation from the reactor vessel. Finally, heat was removed from the containment vessel by air flow from the atmosphere, which is the ultimate heat sink. Both IVR-ERVC and RVACS concepts concentrate on the cooling of vessel and limiting the accident boundary inside of the primary coolant system.

RVACS was adopted in PRISM and its performance satisfied safety criteria [1, 2]. Prototype Generation-IV SFR (PGSFR) which has been developed in Korea also adopted RVACS for decay heat removal. To apply RVACS to the PGSFR, there should be experimental approach to verify performance of RVACS. Considering sodium pool part for the whole heat transfer circuit, PGSFR has large reactor vessel which has larger diameter than 8 m, and sodium, especially liquid sodium has many problems to handle. Therefore, using simulants can has huge advantages in the aspect of handling, economy, visualization.

For scaled-down experiments, or experiments with simulants should match similarity with original phenomena. In so far, natural circulation of liquid metal has been mainly researched as cooling by decay heat removal system (DHRS) which is located inside of the reactor vessel. Takeda et al suggested modified dimensionless parameter as modified Grashof number and modified Boussinesq number for natural circulation of liquid metal [3]. Weinberg et al considered additional parameters required for similarity such as Euler number and Richardson number [4]. Ieda et al summarized behavior of each dimensionless parameters along to scale and simulants material [5]. He concluded that in small scale, water is suitable, however, in real scale, actual liquid metal is suitable for similarity. Experimental loop PHEASANT was also designed by similarity law similar to Takeda et al [6].

However, all these studies were analyzing DHRS, which is regardless with boundary with reactor vessel. In present study, based on similarity law applied on natural circulation by DHRS, similarity law for natural circulation caused by RVACS was studied especially on the boundary type at the reactor vessel; with radiation, without radiation, constant temperature, constant heat flux. Simple CFD example for validation of similarity law was conducted.

2. Similarity analysis

2.1 Derivation of Similarity Law

Thermal-hydraulic characteristics in liquid metal natural circulation have been suggested and confirmed by scale-down experiments of DHRS [2-6]. 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 lefthand 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

2.2 Simulant

Among the various parameters, Grashof (Reynolds) number and Boussinesq (Peclet) number are more important in natural circulation because Grashof number has effect on velocity profile and Boussinesq number has effect on temperature profile. Between two numbers, Boussinesq number is more important because it means temperature profile, which makes deriving force of the natural circulation.

There are three kinds of working fluids which are able to be considered; heat transfer oil, water, and liquid metal. Modified Boussinesq number is in Fig. 1 which various scale.

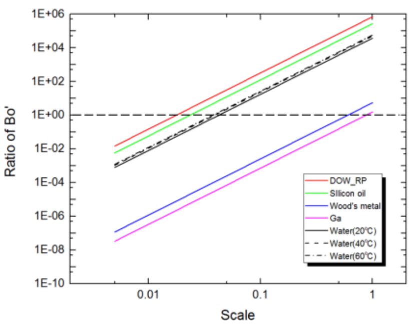


Fig. 1. Ratio of modified Boussinesq number to actual plant for various candidates.

For heat transfer oil, to match modified Boussinesq number, scale should be less than 1/50. Ratio of modified Grashof number has much smaller value than other liquid so that flow regime is significantly changed. Because of highest viscosity and lowest thermal conductivity among the candidates, heat transfer oil is not suitable for working fluids.

Liquid metals (gallium, wood's metal) have similar properties with original coolant, sodium, except for density. These similar properties have some advantages in real scale, however, have disadvantages in scale-down. In the point of visualization, liquid metal is worse than other candidates because of its transparency.

Therefore, water is the best working fluid for scale-down experiments. Fig. 2 represents behavior of each dimensionless parameters of water along scale. The scale was given as 1/25, which is appropriate scale for matching modified Boussinesq number. Prantdl number is only depending on material properties so it is independent to scale. For Richardson number and Euler number, pressure difference is driving force in case of natural circulation. Therefore, as long as pressure drop coefficient maintained, these two numbers are independent to scale. Remained parameters are Reynolds and modified Grashof number, which related to velocity profile. It is two-order smaller than actual, however, it can be admitted as long as turbulent flow is maintained.

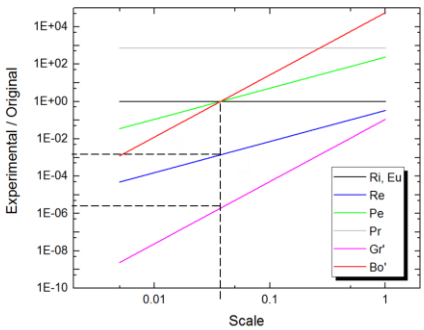
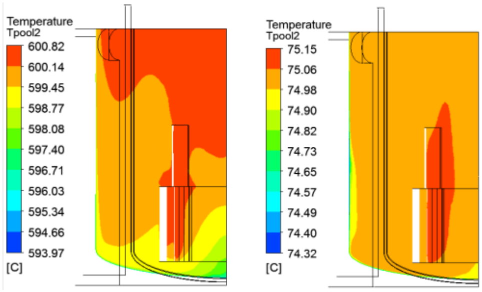


Fig. 2. Ratio of parameters of given scale in case of water.

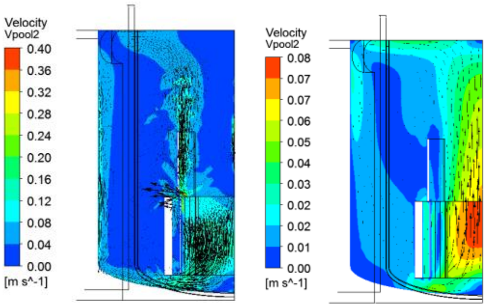
3. CFD analysis

Similarity analysis from the previous chapter was validated by the CFD analysis. 1/4 symmetrical geometry was used. Heat was only generated in the core and removed by the air flow though natural circulation inside of the pool.

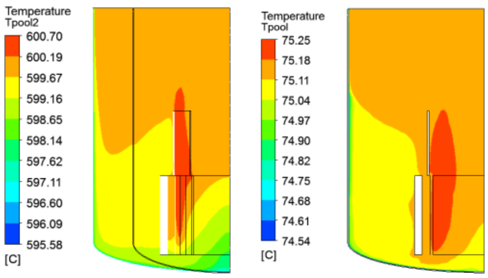
To observe effect of boundary condition on natural circulation inside, two kinds of boundary condition were adopted. For both actual plant case and scale-downed water case, two types of boundary condition had been analyzed; radiative heat transfer for whole geometry, and constant temperature for reactor pool. Constant temperature was applied as about 593.9 ºC and about 74.3 ºC for sodium pool and water pool, which was obtained from the whole with radiation case.



(a) Actual plant - sodium (b) Scaled down - water
Fig. 3. Comparison of temperature profile – with radiation.



(a) Actual plant - sodium (b) Scaled down - water
Fig. 4. Comparison of velocity profile – with radiation.



(a) Actual plant - sodium (b) Scaled down - water
Fig. 5. Comparison of temperature profile – constant T.

Fig. 3 and 4 showed the quite different temperature and velocity distribution of the inside of the wall. It seems similarity law was not working. However, in figure 5, constant temperature applied case, temperature profiles are very similar. Which means similarity law was working.

Main reason for difference in temperature profile was related to radiation. For actual plant, the temperature of the reactor vessel and containment vessel were relatively higher than that of scale-downed water case. Therefore, radiative heat flux, which is proportional to fourth power of the temperature, is dominant. For air duct, water case showed temperature low region near the bottom of the side wall of the vessel. In air duct point of view, this region is just after separator and fresh air supplied to the surface. So, in convective dominant air case, temperature profile at that region was distorted. And in experiment, this should be revised by changing duct geometry.

Another reason for discordance is natural circulation flow. Although temperature profile is driving force of the natural circulation, it is affected by natural circulation also. Stronger upward flow makes that cold coolant penetrated

Table I: Compare of temperature difference and reference temperature difference

	Water	**Sodium**
T_{max}	75.25	600.70
T_{min}	74.54	595.58
ΔT	0.71	5.12
ΔT ratio	**0.14**	
ΔT_{ref}	0.253	1.668
ΔT_{ref} ratio	**0.15**	

Data obtained by scale-down facility can be translated to plant data using reference properties [7]. Actually, reference properties are driven by governing equation and relationship. In other words, it means overall magnitude of certain parameters. Each data can be treated as multiplication of reference properties and deviation. Because deviation can be satisfied by matching non-dimensional number, only reference properties governs ratio of each parameters. Therefore, actual plant parameter can be obtained by multiplying ratio of reference properties to experimental values.

Constant temperature cases, which showed most similar temperature distribution, were selected to verify data interpretation. For interpretation of the temperature, temperature profile of the real scale sodium and that of scale-downed water was similar. And temperature difference similar with temperature ratio. And its ratio of the temperature difference and reference temperature difference showed similar value. It was summarized in Table I. Therefore, experimental data interpretation using reference property can be possible and showed adequate level of accuracy.

4. Conclusions

To determine boundary condition for sodium pool natural circulation by RVACS, similarity law application and CFD analysis were conducted. Similarity analysis about sodium pool natural circulation behavior under RVACS condition was conducted. Water is the best working fluid for reduced scale experiments and 1/25 reduced scale is appropriate for water in the point of modified Boussinesq number.

Because modified Boussinesq number was the same, Overall temperature distribution is similar between actual sodium and scale-downed water. Although Reference properties indicates relative magnitude of the parameter, so experimental data can be interpreted to original plant data by multiplying deviation percentage to ratio of reference property.

Owing to radiation heat transfer, which is dominant in high temperature, there was difference in temperature distribution in whole geometry case. To compensate this effect, similarity laws were verified in constant temperature boundary condition. In real experiment, this kind of temperature distortion by radiation should be compensated by changing geometry of the duct.

Experimental approach will be conducted in near future with 2-D slice test section. Similarity law will also be validated by this experiment.

NOMENCLATURE

c: heat capacity
g: gravitational acceleration
L: Characteristic length
P: Pressure
t: time
T: temperature
u: velocity
x: length scale

β: thermal expansion coefficient
δ: thermal boundary layer thickness
ρ: density

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