Scaling analysis of various simulants for sodium thermal-hydraulic experiment in a reduced-height scale test facility

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1. Introduction

Sodium-cooled Fast Reactor (SFR) is one of the promising reactor types for Generation IV (Gen IV) nuclear reactor technology. During the past decades, several countries with advanced nuclear reactor technology had constructed and operated the SFR, and currently, China, France, India, Korea, and Russia have actively conducted the R&D works for advanced SFR development.

In the design of a SFR safety system, thermal-hydraulic behavior of liquid sodium (Na) flow inside the reactor is essential. Especially in an accident condition, such as LOOP (Loss Of Off-site Power), passive Decay Heat Removal System (DHRS) should be readily operated with sufficient natural circulation sodium flow induced by gravity. Since the natural circulation behavior of a fluid system is determined under the closely coupled mechanism of heat transfer and hydraulic effects, the experimental validation of the natural circulation system based on rigorous scaling analysis is needed. In practice, since the reduced geometrical scaling is unavoidable for simulating the real phenomena in a large-scale reactor, the selection of same fluid (sodium) as an experimental working fluid would be recommended for reliability and simplification of the analysis and application of the experimental results. However, in the lab-scale experiments by academic or small research group, it is difficult to use liquid sodium as a working fluid due to the risk of sodium-water reaction (SWR) and thereby high safety cost. Hence, the use of simulant fluids and its examination in terms of scaling effect are required.

In this study, we simply introduce the scaling analysis method for single-phase natural circulation system, and investigate the scaling characteristics of various simulants for practical application as working fluids.

2. Methods and Results

First of all, we postulate a simple loop of single-phase natural circulation with a heating region, a cooling region, and the pipe lines (Fig. 1). In this loop, the natural circulation flow is generated by gravity effect due to the density difference between the heating and cooling regions placed in lower and higher positions, respectively. For establishing the non-dimensional mass, momentum, and energy conservation equations, and deriving the key similarity parameters, we utilized the one-dimensional and single-phase dimensional analysis approach by Heisler [1], and Ishii and Kataoka [2].

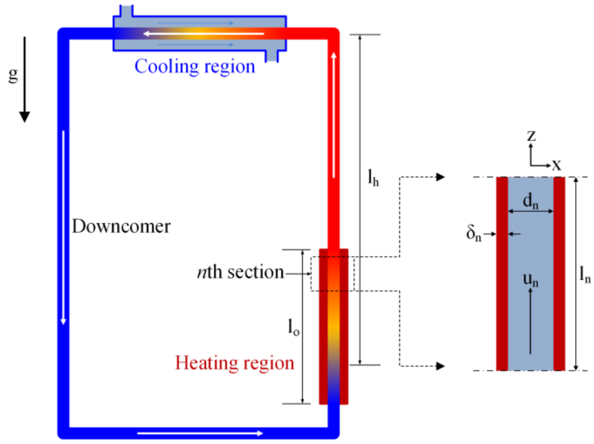

Fig. 1. Schematics of a single-phase natural circulation loop.

2.1 Scaling analysis

Eq.(1)-(5) are the one-dimensional simplified conservation equations and the boundary condition [2].

Continuity equation

$$u_n = \frac{a_o}{a_n} u_r \quad (1)$$

Integral momentum equation

$$\rho \frac{du_r}{dt} \sum_n \frac{a_o}{a_n} l_n = \rho g \beta \Delta T l_h - \frac{\rho u_r^2}{2} \sum_n \left(\frac{fl}{d} + K \right)_n \left(\frac{a_o}{a_n} \right)^2 \quad (2)$$

Fluid-side energy equation for *n*th section

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial z} \right) = \frac{4h}{d} (T_s - T) \quad (3)$$

Solid-side energy equation for *n*th section

$$\rho_s c_{ps} \frac{\partial T_s}{\partial t} + k_s \nabla^2 T_s - \dot{q}_s = 0 \quad (4)$$

Boundary condition at the solid-liquid interface

$$-k_s \frac{\partial T_s}{\partial x} = h(T_s - T) \quad (5)$$

where u, a, ρ, t, g, β, ΔT, l, d, f, K, c_p, T, h, k, and $\dot{q}_s$ are the fluid velocity, cross-sectional area, density, time, gravity acceleration, volume expansion coefficient, fluid temperature rise, length, hydraulic diameter, friction factor, minor loss coefficient, specific heat capacity, temperature, heat transfer coefficient, thermal conductivity, and volumetric heat generation rate inside solid, respectively. And, subscripts o, r, h, and s denote the reference constant value, representative variable, heating region, and solid, respectively. From the above five equations, we can obtain the non-dimensional equations, and then the key similarity groups can be defined in Table I.

Table I. Non-dimensional numbers for the similarity

Richardson number	$Ri \equiv g\beta \Delta T_o l_o / u_o^2$
Friction number	$F_n \equiv \left(fl/d + K \right)_n$
modified Stanton number	$St_n \equiv \left(4hl_o / (\rho c_p u_o d) \right)_n$
Time ratio number	$T_n^* \equiv \left(\alpha_s l_o / (\delta^2 u_o) \right)_n$
Biot number	$Bi_n \equiv \left(h\delta / k_s \right)_n$
heat source number	$Q_{sn} \equiv \left(\dot{q}_s l_o / (\rho_s c_{ps} u_o \Delta T_o) \right)_n$

where α_s and δ are the thermal diffusivity of solid and the conduction (wall) thickness in heating region. In addition to Table I, non-dimensional axial scales, $L_n = l_n / l_o$ and $L_h = l_h / l_o$, and cross-sectional flow area scale, $A_n = a_n / a_o$ can be defined. In Table I, the reference velocity (u_o) and temperature rise (ΔT_o) scales are utilized, and those should be obtained in advance for the scaling analysis. Ishii and Kataoka [2] had presented the solutions for u_o and ΔT_o by setting the heating region as a representative section. Thus, the solution of u_o could be obtained with steady-state calculation of Eq. (2), and that of ΔT_o was given by steady-state energy balance consideration between solid and fluid regions

$$u_o = \left\{ \beta \left(\frac{\dot{q}_o l_o}{\rho c_p} \right) l_h \left(\frac{a_{so}}{a_o} \right) / \left(\frac{1}{2g} \sum_n \frac{F_n}{A_n^2} \right) \right\}^{1/3}, \quad (7)$$

$$\Delta T_o = \frac{\dot{q}_o l_o}{\rho c_p u_o} \left(\frac{a_{so}}{a_o} \right), \quad (8)$$

where a_s is the solid cross-sectional area.

For satisfying complete similarity between model and prototype systems, the ratio of dimensionless numbers in Table I should be

$$Ri_R = F_{nR} = St_{nR} = T_{nR}^* = Bi_{nR} = Q_{snR} = 1 \quad (9)$$

where subscript R denotes the ratio of model to prototype.

Assuming that the similarity condition, $F_{nR} = 1$ can be unconditionally satisfied by inserting suitable orifice into the model loop, the geometrical similarities for the axial length ($L_{nR} = 1$) and flow cross-sectional area ($A_{nR} = 1$) give the complete kinematic and dynamic similarity. In this case, by substituting Eq. (10) and (11) into Eq. (12), $Ri_R = 1$ can be automatically established.

$$u_{oR} = \frac{u_{om}}{u_{op}} = \left\{ \dot{q}_{oR} \left(\frac{\beta}{\rho c_p} \right)_R \frac{\delta_{oR}}{d_{oR}} l_{oR}^2 \right\}^{1/3}, \quad (10)$$

$$\Delta T_{oR} = \frac{\Delta T_{om}}{\Delta T_{op}} = \dot{q}_{oR} \left(\frac{1}{\rho c_p} \right)_R \frac{l_{oR}}{u_{oR}} \frac{\delta_{oR}}{d_{oR}}, \quad (11)$$

$$Ri_R = \beta_R \Delta T_{oR} l_{oR} \frac{1}{u_{oR}^2}. \quad (12)$$

where subscripts m and p denote the model and prototype.

In the next stage, the energy similarity conditions ($St_{nR} = T_{nR}^* = Bi_{nR} = Q_{snR} = 1$) should be considered. It is noted that the Stanton number similarity is automatically satisfied when other three requirements for T_{nR}^*, Bi_{nR}, and Q_{snR} are established. Through using the same solid materials between the model and prototype, and satisfying the above geometrical similarities, we can the detailed energy similarity conditions

$$T_{nR}^* = l_{oR} / (u_{oR} / \delta_{nR}^2) = 1, \quad (13)$$

$$Bi_R = h_R \delta_{nR} = 1, \quad (14)$$

$$Q_{soR} = (\rho c_p)_R d_{oR} / \delta_{oR} = 1. \quad (15)$$

From eqs. (13)-(15), the scaling ratios for key parameters can be obtained

$$\delta_R = \sqrt{\frac{l_R}{u_R}}, \quad (16)$$

$$d_R = \frac{1}{(\rho c_p)_R} \sqrt{\frac{l_R}{u_R}}, \quad (17)$$

$$u_R = (\dot{q}_R \beta_R l_R^2)^{1/3}, \quad (18)$$

$$\Delta T_R = \dot{q}_R \frac{l_R}{u_R}, \quad (19)$$

$$t_R = \frac{l_R}{u_R}\,, \tag{20}$$

$$h_R = \frac{1}{d_R} = \sqrt{\frac{u_R}{l_R}}\,. \tag{21}$$

where t_R is the time scaling ratio, and subscript o was omitted for simplicity.

The heat transfer coefficient scaling ratio in Eq. (21), h_R is closely related to the temperature change across the thermal boundary layer at liquid-solid interface in the heating region, and the value is a strong function of the flow structure and fluid thermo-physical properties. Generally, a correlation for h is represented in terms of the Nusselt number, $Nu \equiv hd/k$. In this study, through the approximation of the laminar flow or the liquid metal flow with low velocity, it is assumed that the Nu is a constant value. From this assumption, the real scaling ratio of the heat transfer coefficient can be determined as Eq. (22). Therefore, for the experimental design of reduced-scale model, the heat transfer similarity by Eqs. (21) and (22) should be carefully considered.

$$h_{R,cor} = \frac{k_R}{d_R} = (\rho c_p k)_R \sqrt{\frac{u_R}{l_R}} \tag{22}$$

2.2 Selection of various simulant fluids

In this study, for selecting the simulant fluids of liquid sodium, melting and boiling point, toxicity, fluid-to-water reactivity, procurement cost, and thermo-physical properties with termperature were considered. The selected simulants are water (H_2O), Galinstan (Ga-In-Sn eutectic alloy), Lead-Bismuth eutectic (LBE, Pb-Bi), Bismuth (Bi), Tin-Bismuth alloy (Sn-Bi), Gallium (Ga), Tin (Sn), and Dowtherm A fluid by Dow company. All fluids except water and Dowtherm A [3-8] are liquid metals. Table II shows the thermo-physical properties of the simulants, and the property data were selected as the values at atmospheric pressure and moderate temperature range between the boiling and melting points. In this table, T_m and T_b are the melting and boiling point of the material.

Table II. Thermo-physical properties of selected simulants

	T_m (°C)	T_b (°C)	ρ (kg/m^3)	β (1/K)	c_p (J/kgK)	k (W/mK)
Sodium [3] ($T = 500^{o}$C)	97.8	889.8	831.8	0.000285	1264.5	69.3
Water [4] ($T = 60^{o}$C)	0	100	983.2	0.000535	4185	0.65
Galinstan [6] ($T = 300^{o}$C)	-19	1300	6332	0.000123	295	35.5
LBE, Pb-Bi [3] ($T = 500^{o}$C)	127.5	1638	10102.7	0.000113	141.4	13.9
Bi [3] ($T = 500^{o}$C)	271.4	1551.8	9749.9	0.000143	135.4	14.7
Sn-Bi [4] ($T = 300^{o}$C)	139	> 526.8	8504.6	0.000163	213	16.6
Ga [5] ($T = 300^{o}$C)	29.8	2400	5893.3	0.000105	385.2	44.1
Sn [7] ($T = 500^{o}$C)	231.9	2602	6798	0.0000953	240	30
Dowtherm A [8] ($T = 150^{o}$C)	12	257.1	952.2	0.00093	1940	0.118

2.3 Scaling analysis results for the various simulants

For the reduced-scale experiment of a large-scale thermo-hydraulic system, the preceded determination of length scaling ratio, l_R is necessary, and also the available heating power is an important factor for the experimental design. In this study, for observing the scaling behaviors on the various simulants, the following assumptions are given as

- $l_R = 0.1$

- $\dot{q}_{oR} = 1$

- same solid material usage

Fig. 2 shows the scaling ratios of velocity and the temperature rise for the simulants. From Eq. (18), the natural circulation velocity and the temperature rise scales of a fluid strongly depend on β_R. The two parameters in the model experiments would be significantly lower than those in the prototype as well. Fig. 3 shows the scaling ratios of the conduction thickness and the hydraulic diameter. Both δ_R and d_R values are smaller than the unity in all test simulants, i.e. for thermal-hydraulic similarity condition, the thickness of the heating wall and the hydraulic diameter should be reduced in the design of model experiments. Especially in the case of water, the hydraulic diameter is significantly smaller than that of the prototype. In the reduced-scale experiment, it can rise an excessive scale reduction problem, and the unconditional satisfaction for friction number similarity might not be achieved in a sodium-to-water simulation experiment.

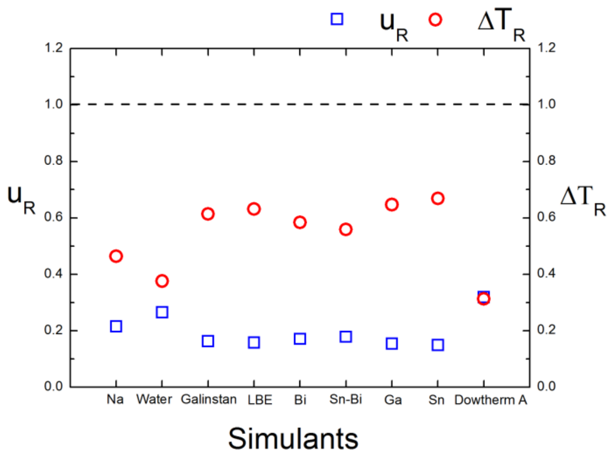

Fig. 2. Scaling ratios of Velocity (u_R) and temperature rise (ΔT_R) for various simulants.

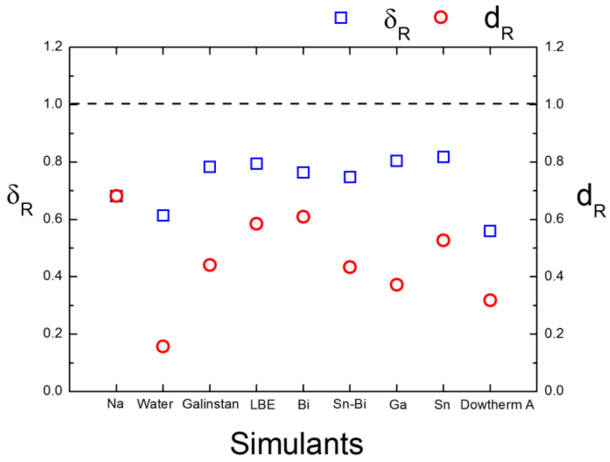

Fig. 3. Scaling ratios of conduction thickness (δ_R) and hydraulic diameter (d_R) for various simulants.

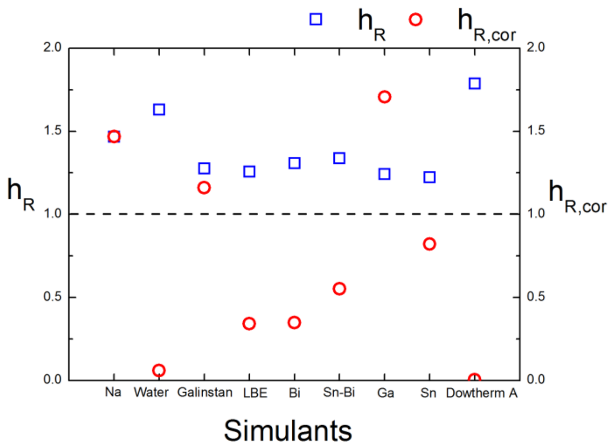

Fig. 4. Scaling ratios of the heat transfer coefficient by the Biot number similarity (h_R) and general correlation ($h_{R,cor}$).

Fig. 4 shows the scaling ratios of the heat transfer coefficients by the Biot number similarity and general correlation. Although the h_R according to the Biot number similarity is larger than the unity in all candidate fluids due to the reduction of hydraulic dimeter, the practical values ($h_{R,cor}$) of the heat transfer coefficient scaling ratios obtained from the calucations with water, LBE, Bi, Sn-Bi, and Dowtherm A is significantly lower than the unity. It comes mainly from the thermal conductivity values of the simulants. Particularly in the cases of water and Dowtherm A, the values of $h_{R,cor}$ drastically decreased when compared to those of other liquid metal simulants. Therefore, although the fluids, such as water and Dowtherm A have easier operability and accessibility, the utilization of the fluids as the simulants for the SFR natural circulation experiments requires more special attention in terms of the thermal-hydraulic similarity. And, $h_{R,cor}$ values of Galinstan, Ga, and Sn showed the relative similarity to the h_R values of them.

3. Conclusions

In this study, the thermal and hydraulic scaling characteristics of various simulants were investigated for the purpose of replicating natural circulation system in an SFR. Since the natural circulation phenomenon is generated by the closely coupled effects of both hydrodynamic and thermal behaviors of working fluid, the attentive selection of the simulant fluids based on the rigorous scaling considerations is needed. And, since these works were based on the simple one-dimensional approach, CFD analyses for verifying the results obtained from this study would be recommended as a future work.

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