Scaling analysis of various simulants for reduced-scale thermal-hydraulic experiment of SFR

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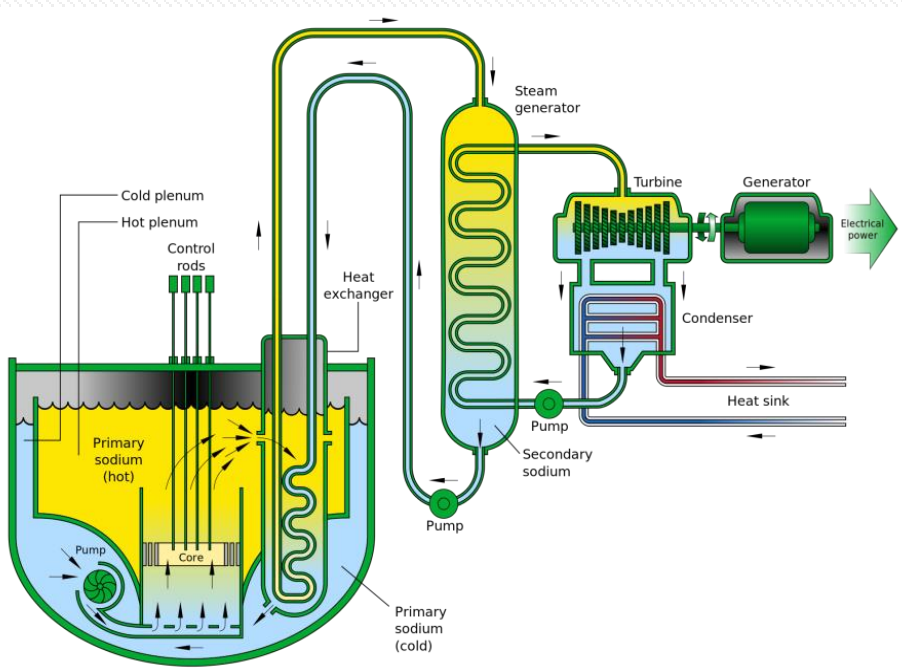
Introduction

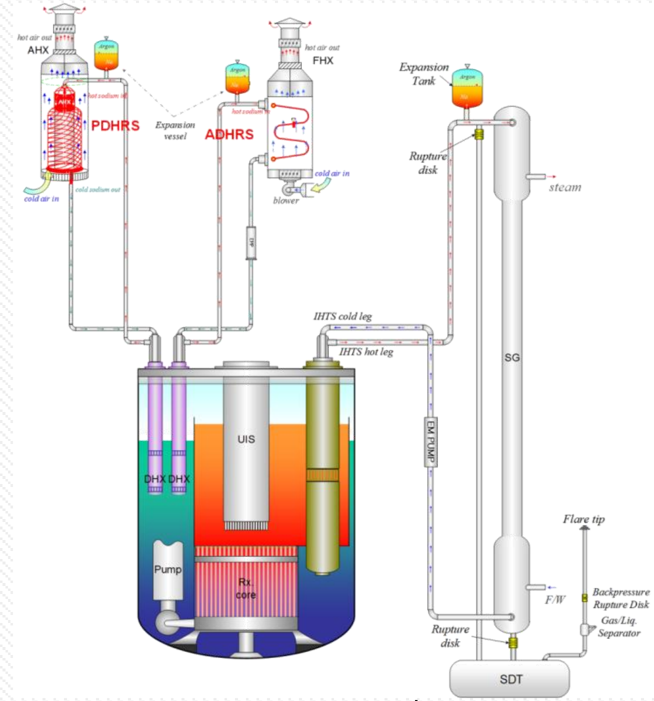
*PGSFR: Prototype Gen-IV SFR

Sodium-cooled Fast Reactor (SFR)



[SFR schematic]

Korea

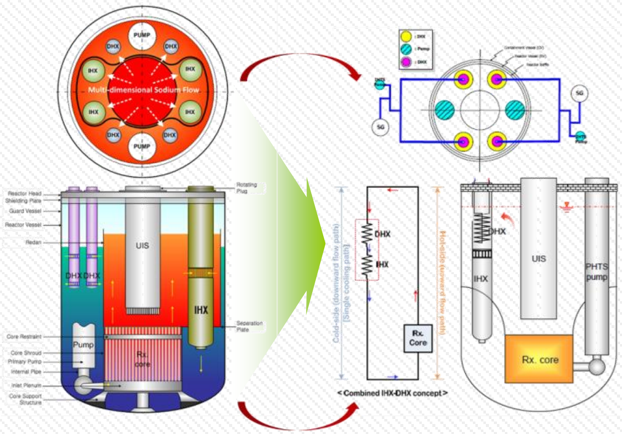


[PGSFR*]

- **SFR** is one of the promising reactor types for **Gen-IV nuclear reactor** technology.
- Recently, **China, France, India, Korea, and Russia** have actively conducted R&D works for advanced SFR development.

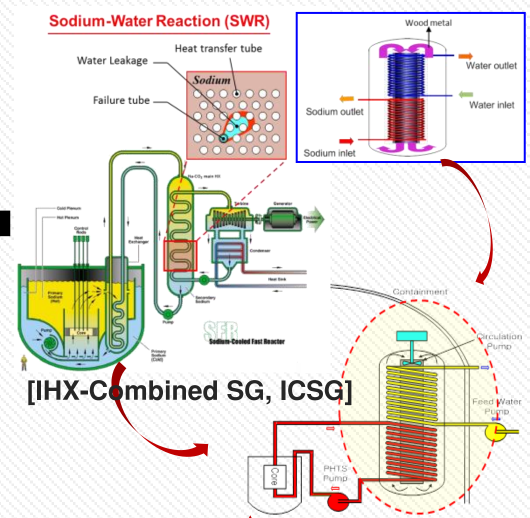
Introduction

Advanced Research Center for Nuclear Excellence



[Combined IHX-DHX unit, CHX]

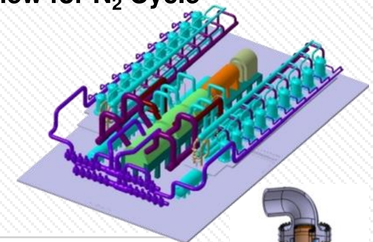
+

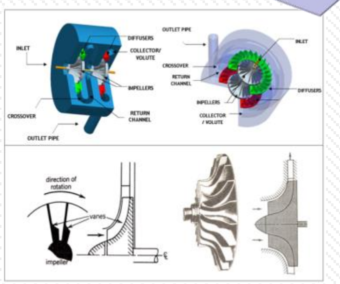


[IHX-Combined SG, ICSG]

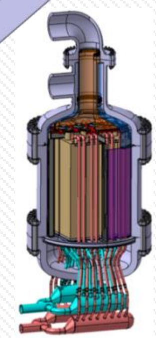
+

Sample ISO view for N_2 Cycle





N_2 Cycle Turbo-machineries (example)



Sodium-N_2 HX

KAERI
POSTECH
KNU
SFR R&D Center

Introduction

Research motivations and objectives

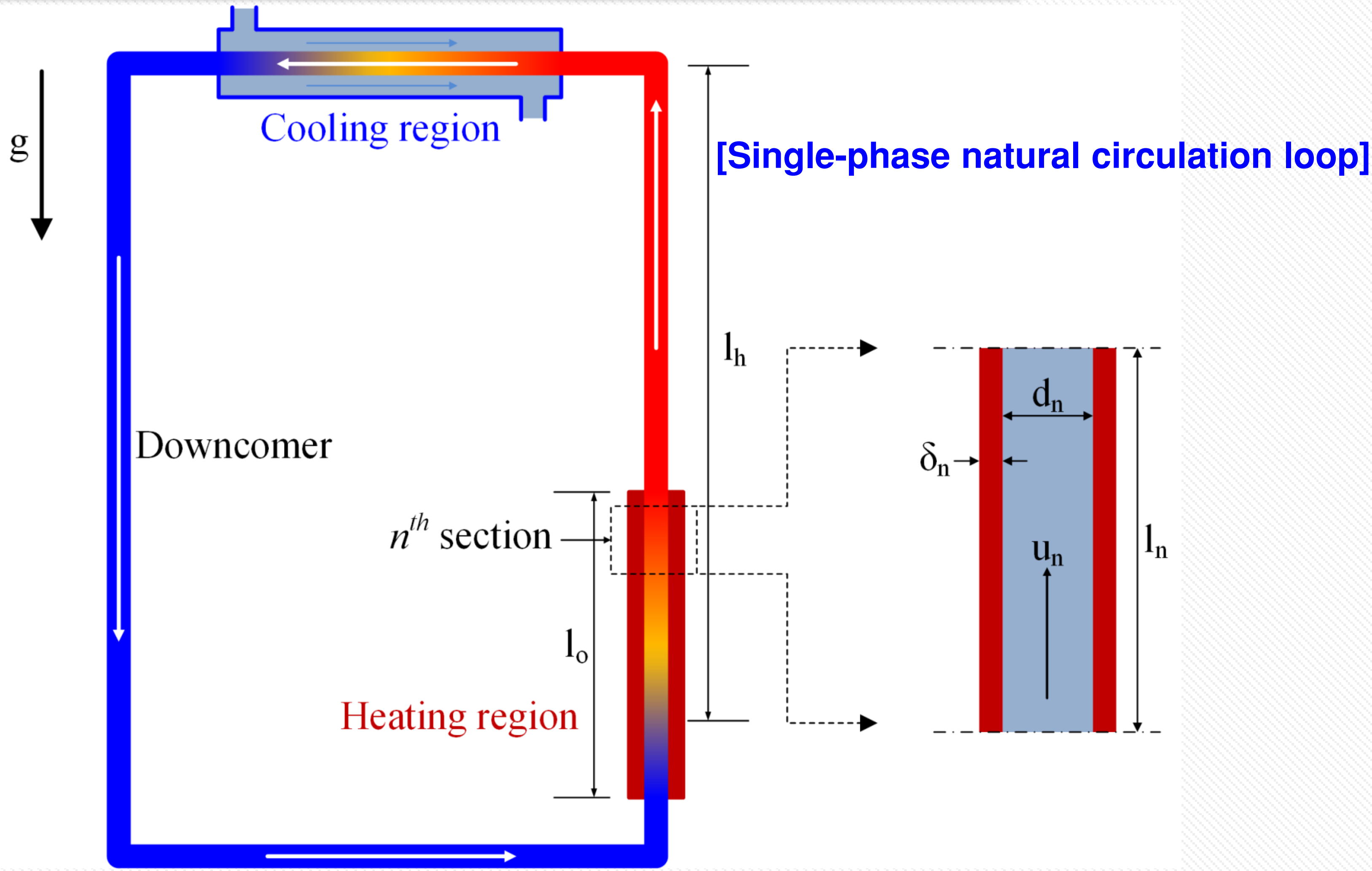
- Motivations
  - In the design of a S… …uid sodium(Na) flow insi…
  - In an accident condi… …uld be readily operate… …ow induced by gravity.
  - Intrinsically, NC behavior of a fluid is determined under the closely coupled mechanism of heat transfer and hydraulic effect.
  - For reduced-scale experimental validation of the NC loop, rigorous scaling analysis is necessary. → Usage of sodium as working fluid is recommended.
  - In lab-scale experiments, it is difficult to use sodium as a working fluid due to SWR(sodium-water reaction) risk and thereby high safety cost.
  - The use of simulant fluids and its examination in scaling effect are required.

Research objectives

1. Simple introduction of scaling analysis method for single-phase natural circulation system
2. Investigation of the scaling characteristics by the application of selected various simulants

Methods

Simple NC loop for scaling analysis



Methods

Scaling analysis

- For establishing non-dimensional continuity, momentum and energy conservation equations, and key similarity parameters, the one-dimensional and single-phase dimensional analysis approach by Heisler [1], and Ishii & Kataoka [2] is utilized.

- One-dimensional simplified conservation equations and B.C.

$$u_n = \frac{a_o}{a_n} u_r$$

Continuity equation

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

Integral momentum equation

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

Fluid-side energy equation for nth section

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

Solid-side energy equation for *n*th section

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

Boundary condition at the solid-liquid interface

Methods

Scaling analysis

- **From the five equations, the non-dimensional equations and the key similarity groups can be defined.**
- **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	$Q_{sn} \equiv \left(\dot{q}_s l_o/(\rho_s c_{ps} u_o \Delta T_o)\right)_n$

$$L_n = l_n / l_o$$

$$A_n = a_n / a_o$$

Methods

Scaling analysis

- **For satisfying complete similarity between model and prototype systems,**

$$Ri_R = F_{nR} = St_{nR} = T^*_{nR} = Bi_{nR} = Q_{snR} = 1$$

- $F_{nR} = 1$ **can be unconditionally satisfied by inserting suitable orifice.**

- **By geometrical similarities for axial length (** $L_{nR} = 1$**) and flow cross-sectional area (** $A_{nR} = 1$**),**

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

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

substitution →

$$Ri_R = \beta_R \Delta T_{oR} l_{oR} \frac{1}{u_{oR}^2}$$

automatically →

$$Ri_R = 1$$

Methods

Scaling analysis

- **Energy similarity conditions**

$$St_{nR} = T^*_{nR} = Bi_{nR} = Q_{snR} = 1$$

- **The Stanton number similarity is automatically satisfied when $T^*_{nR} = Bi_{nR} = Q_{snR} = 1$.**

- **Through using the same solid materials between the model and prototype, and satisfying the geometrical similarities, the energy similarity conditions can be obtained.**

$$T^*_{nR} = l_{oR} / (u_{oR} / \delta^2_{nR}) = 1$$

$$Bi_R = h_R \delta_{nR} = 1$$

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

Methods

Scaling analysis

- **Scaling ratios for key parameters**

$$\delta_R = \sqrt{\frac{l_R}{u_R}}$$

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

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

$$\Delta T_R = \dot{q}_R \frac{l_R}{u_R}$$

$$t_R = \frac{l_R}{u_R}$$

$$h_R = \frac{1}{d_R} = \sqrt{\frac{u_R}{l_R}}$$

→ **Heat transfer coefficient is not only function of geometry, but also a strong function of the flow structure and fluid thermo-physical properties.**

- **Applying the approximation of the laminar flow or the liquid metal flow with low velocity, the real scaling ratio of the heat transfer coefficient can be determined**

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

Results

Selection of various simulant fluids

- **Melting and boiling points, toxicity, fluid-to-water reactivity, commercial availability, and database availability of thermo-physical properties were considered.**

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

Results

Introduction of selected simulants

Galinstan (Ga-In-Sn alloy)

A substitute for toxic Mercury

Non-toxicity, non-reactiviy

An efficient coolant

High prices

An aggressive metal

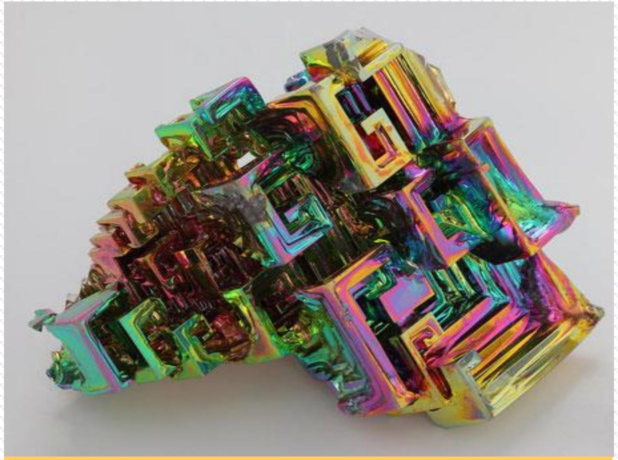
Lead-Bismuth Eutectic (Pb-Bi)

Used as a coolant for NPP

Do not react readily with water

Corrosive to steel

Lead is highly toxic.



Bismuth (Bi)

A substitute for lead

Do not react with water

Non-corrosive to steel

Non-toxicity

Results

Introduction of selected simulants

Bismuth Tin alloy (Sn-Bi)

Used as solder

Non-toxicity and non-reactivity

Non-corrosive to steel

Gallium (Ga)

High prices

Application to semiconductors

Non-toxicity, non-reactivity, and non-corrosive to steel

Tin (Sn)

Used from the Bronze Age

Low prices

Used in alloys with lead as solder

Non-toxicity, non-reactivity

Not attack steel below 400 C

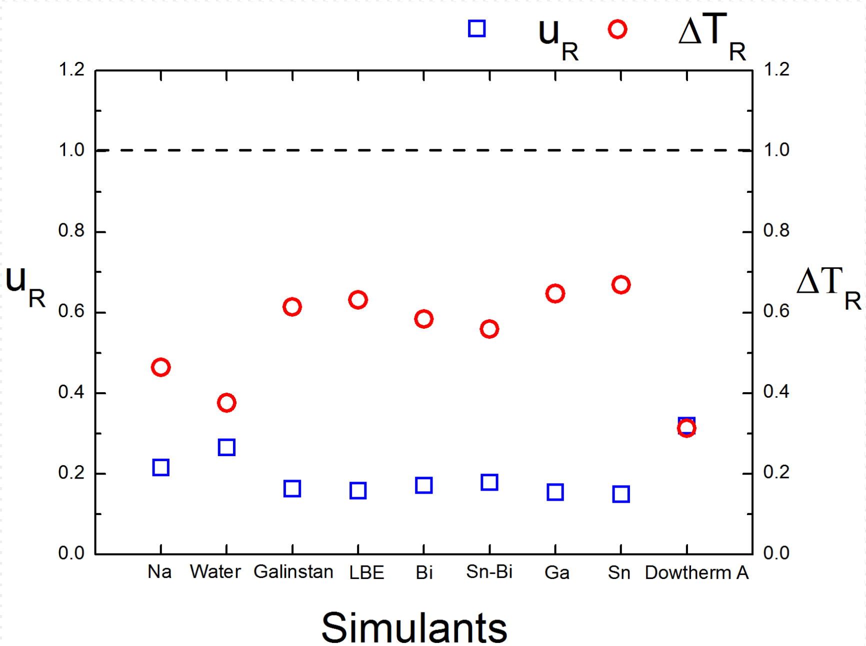
Results

Scaling analysis results for the simulants

- **Length and power scaling ratio**

$l_R = 0.1$ $\dot{q}_{oR} = 1$ **Same solid material usage**

- **Scaling ratios of velocity and temperature rise for the simulants**

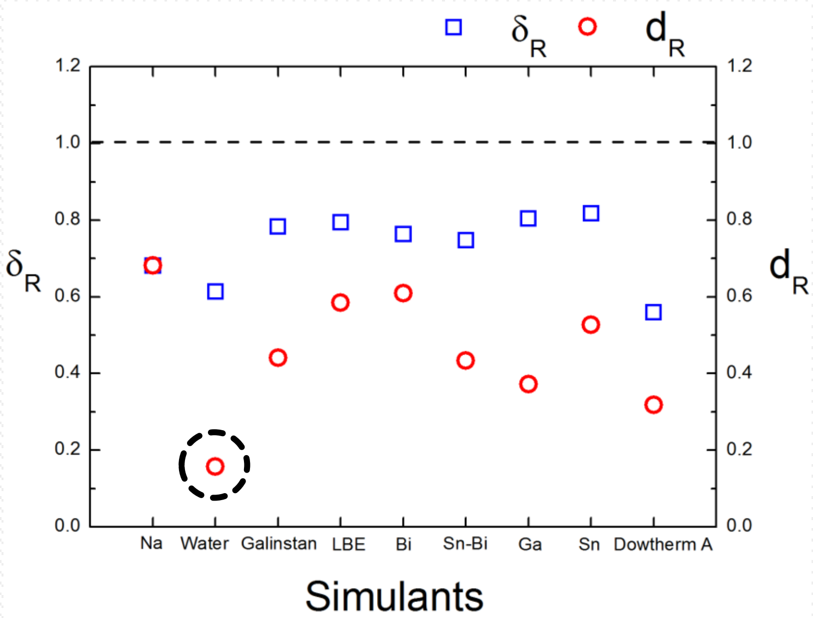


- **The natural circulation velocity and the temperature rise scales strongly depend on β_R.**
- **Two parameters in the model exp. would be significantly lower than those in the prototype.**

Results

Scaling analysis results for the simulants

- **Scaling ratios of the conduction thickness and the hydraulic diameter**



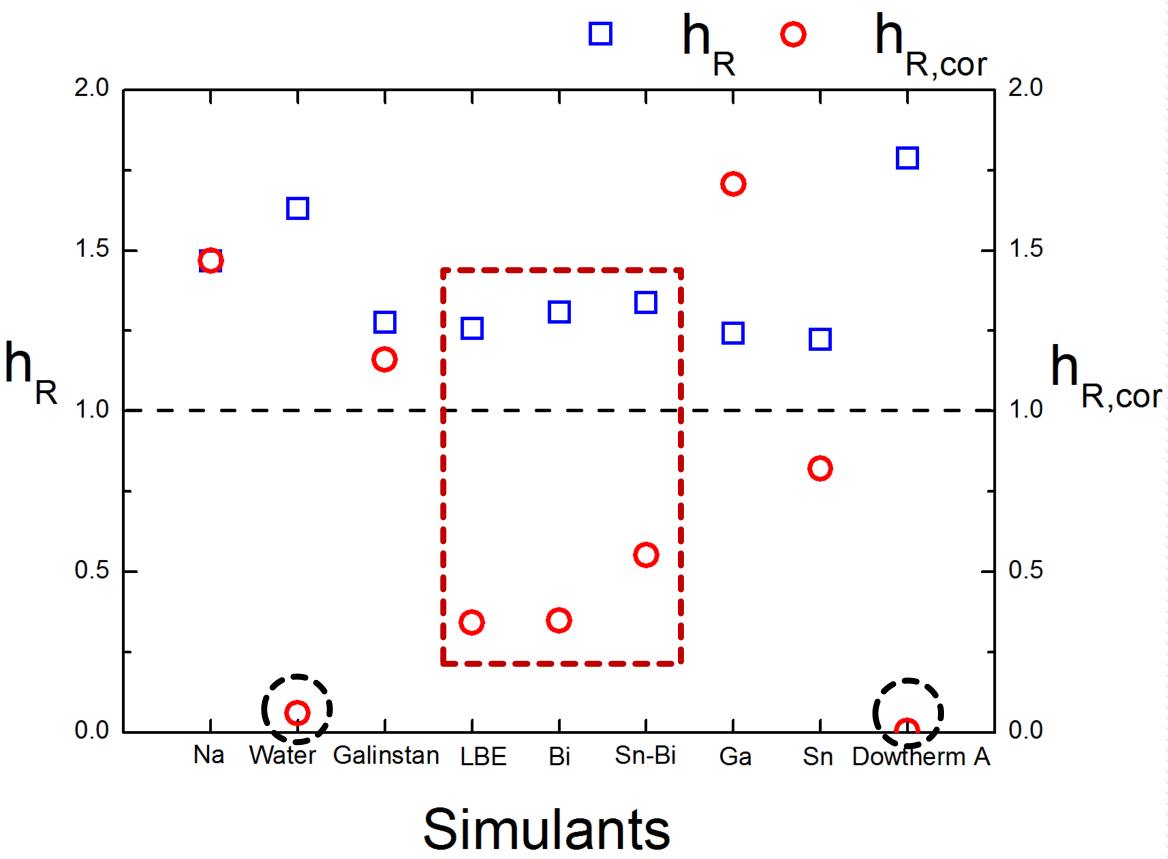
- **For thermal-hydraulic similarity condition, the thickness of the heating wall and the hydraulic diameter should be reduced in the model exp. design.**
- **Especially, in the case of water, the hydraulic diameter is significantly smaller than that of the prototype.**

- **In the reduced scale exp., it can rise an excessive scale reduction problem.**
- **And, unconditional satisfaction for friction number similarity might not be achieved in a Na-water simulation exp..**

Results

Scaling analysis results for the simulants

- **Scaling ratios of the heat transfer coefficients by Biot number similarity and general correlation**



Distortion of scaling mainly by thermal conductivity difference

Conclusions

Conclusions and future work

- In this study, the thermal and hydraulic scaling characteristics of various simulants were investigated for the SFR NC system.
- Since natural circulation phenomenon is generated by the closely coupled effects of both hydraulic and thermal behaviors of working fluid, the reasonable selection of the simulant fluid based on the rigorous considerations is needed.
- Water and Dowtherm A as the simulant fluids for SFR simulation seem to be inadequate due to their much lower thermal conductivity than Na, despite of their easier operability and accessibility.
- At the view of scaling of heat transfer coefficient, it can be predicted that the scaling distortions of Galinstan, Gallium, and Tin(Sn) would be relatively smaller than those of other liquid metals.
- As a future work, CFD analysis for comparing to the results of this study would be performed.

References

Ref.

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Thank you.

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