Scaling Method for Lead-Bismuth Natural Circulation Under Marine Rolling Conditions

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Abstract

Lead-bismuth fast reactors have broad application prospects in the field of marine power. The thermal-hydraulic characteristics of Lead-Bismuth Eutectic (LBE) under marine conditions have a significant effect on the reactor safety. A new scaling analysis method for the LBE natural circulation under rolling conditions was derived to understand the corresponding mechanism. The design criterion for the scaled-down facility was obtained and the influence of varying rolling processes with different amplitudes and periods was discussed. The numerical models were simulated using Fluent code to verify the scaling criterion. The results show that the time-averaged parameters of the LBE prototype under different rolling processes can be accurately simulated by the scaled-down model, with a maximum error of less than 9.08%. The scaled-down cases reflected the periodic changes of the flow characteristics in the prototype. The low-flow phases caused by the instability during the rolling motion led to the periodic brief scaling distortion of the mass flow rate. In addition, the transient deviation of the temperature difference decreases with the reduction of the rolling amplitude and period. These conclusions have important application value for the design of the LBE experimental device under the marine motion.

Full Text

Preamble

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Lead-bismuth fast reactors have broad application prospects in the field of marine power. The thermal-hydraulic characteristics of Lead-Bismuth Eutectic (LBE) under marine conditions have a significant effect on reactor safety. A new scaling analysis method for LBE natural circulation under rolling conditions was derived to understand the corresponding mechanism. The design criterion for the scaled-down facility was obtained, and the influence of varying rolling processes with different amplitudes and periods was discussed. Numerical models were simulated using Fluent code to verify the scaling criterion. The results show that the time-averaged parameters of the LBE prototype under different rolling processes can be accurately simulated by the scaled-down model, with a maximum error of less than 9.08%. The scaled-down cases reflected the periodic changes of the flow characteristics in the prototype. The low-flow phases caused by instability during rolling motion led to periodic brief scaling distortion of the mass flow rate. In addition, the transient deviation of the temperature difference decreases with the reduction of the rolling amplitude and period. These conclusions have important application value for the design of LBE experimental devices under marine motion.

Keywords: Marine reactor, Rolling condition, Lead-bismuth eutectic, Natural circulation system, Scaling analysis method

Nomenclature

List of Symbols
Cross-section area
Pipe diameter
Total circulation length
Fluid velocity
Modified acceleration
Fluid temperature of hot and cold section
Density
Thermal expansion coefficient
Centripetal and Tangential acceleration
Height between cooling heating section center
Friction loss coefficient
Temperature difference
Dynamic viscosity
Dimensionless time correction factor
Angular velocity
Angular acceleration
Rotation angle
Rolling period
Form loss coefficient
Specific heat capacity at constant pressure

Rolling radius
Heat flux
Axial length of heating and cooling section
Thermal conductivity of solid wall
Thermal conductivity

Subscripts
Ratio between the scaled-down model and prototype
Theoretical value
Reference constant

Abbreviations
Natural Circulation Loop-Shanghai Jiaotong University
Richardson number
Friction number
Heat source number
Stanton number
Reynolds number
Lead-Bismuth Eutectic
Thermal-hydraulic ADS Lead-bismuth Loop
CHEmical OPErational transient
Lead-bismuth eutectic Experimental Circulation facility under Ocean conditions
Core Makeup Tank
Heavy Liquid Metal
User-Defined Function
Shear Stress Transport

INTRODUCTION

The lead-based fast reactor is one of the six types of Generation-IV advanced reactors. Lead-Bismuth Eutectic (LBE) has a low melting point, a high boiling point, outstanding heat transfer and neutron characteristics, and stable chemical properties, making it a promising candidate coolant for advanced reactor systems [?]. For small-scale and specialized applications such as ocean and deep-sea exploration, the lead-bismuth fast reactor represents a viable option [?, ?].

The additional forces imposed by ocean conditions on fluids lead to complex spatial dynamics, such as inclination, heaving, and particularly rolling motions [?]. As ocean and floating nuclear power continue to develop [?], changes in flow and heat transfer characteristics under marine conditions have attracted increasing attention [?].

Zhang et al. [?] analyzed the pressure drop of single-phase flow in horizontal pipe sections under rolling motion and developed a frictional factor correlation. Yan et al. [?] fully considered the channel structure and adopted a 3×3 rod bundle test section to study the pressure drop characteristics of forced air-water two-phase flow under rolling conditions. The study pointed out that the flow rates of gas and liquid were important influencing factors for dynamic frictional resistance in the rod bundle. Meanwhile, the rolling amplitude had a significant influence on the two-phase frictional pressure gradient, while that of the period was relatively small. Yan and Gu et al. [?] adopted CFD code to analyze the influence of rolling motion on flow and heat transfer characteristics of turbulent flow in typical rod bundles. For short-period and large-amplitude cases, the additional force has a significant impact on flow characteristics, and the correlation of frictional resistance and heat transfer coefficient under steady state is no longer reliable. Bai et al. [?] studied the flow characteristics of the helical coil once-through steam generator in floating nuclear power plants. The improved Relap5 code was used to investigate the influence of rolling motion. In addition to local phenomena, significant attention has also been paid to the thermal-hydraulic characteristics of natural circulation within integral facilities under ocean conditions.

Tan et al. [?] pointed out that rolling inertial force leads to an increase in the resistance coefficient of the natural circulation loop, thus reducing the average flow rate. Cong et al. [?] discussed the influence of rolling motion on the stability of the natural circulation system. The study indicated that the swing period, maximum swing angle, swing phase difference, and heat power have significant impacts on the system, while the swing radius has little impact. Wang et al. [?] classified the flow instabilities of the system under ocean conditions and discussed the characteristics of density wave oscillations under natural circulation. Resonance phenomena should be avoided to enhance system stability.

To study the thermal-hydraulic characteristics of LBE, many experimental facilities have been built, such as the KYLIN-II experimental loop [?, ?], the Thermal-hydraulic ADS Lead-bismuth Loop (TALL) experimental facility [?], the Chemical Operational transient (CHEOPE) facility [?], and the Natural Circulation Loop-Shanghai Jiaotong University (NCL-SJTU) facility [?], among others. Researchers at Xi' an Jiaotong University built the Lead-bismuth Eutectic experimental Circulation facility under Ocean conditions (LECO) [?]. The influence of marine conditions on forced circulation flow and resistance characteristics of LBE was studied based on the rolling bench and CFD codes [?]. The majority of existing facilities are designed for stationary and land-based conditions. Therefore, further research on the thermal-hydraulic characteristics of LBE flow under motion conditions is crucial for the development of oceanic LBE reactors.

Considering factors such as site, cost, and safety, experimental facilities cannot reproduce the full-scale reactor and its associated ships and ocean environment. It is typically used in engineering to obtain a set of scaling methods and establish experimental facilities based on these methods. Over the years, many researchers have conducted extensive studies on scaling theory. Theories such as linear analysis [?], power-volume analysis [?], Hierarchical Two-Tiered Scaling

(H2TS) [?], and Dynamical System Scaling (DSS) [?] have been proposed. A wealth of scaling methods has been gradually developed and widely applied to the analysis of land-based nuclear reactors based on the above theories.

In recent years, Li et al. [?] derived corresponding scaling methods respectively for single-phase natural circulation in a rectangular loop and the gravity-driven drainage phenomenon in the core makeup tank (CMT) based on H2TS and DSS theories. The Relap5 code was used to establish system models [?]. Xu et al. [?, ?] conducted scaling analysis on the transient process of natural circulation in pressurized water reactor systems, and the study compared differences among several methods.

However, research on scaling analysis of small heavy liquid metal (HLM) reactors under marine conditions is relatively lacking. In recent years, Zhao et al. [?] explored the rationality of using scaled loops to study LBE natural circulation fast reactors, but the research was based on steady-state parameters. Xu et al. [?] developed scaling methods for the transient process of LBE circulation. Similar to previous studies, their work limited consideration of the dynamic process to power varying with time under land conditions. In this study, scaling research on LBE natural circulation under marine rolling motions was conducted. Considering the influence of additional forces, a scaling method was developed for dynamic LBE natural circulation under rolling motion based on H2TS theory. Numerical simulations of rolling processes were conducted using Fluent to verify the accuracy of the scaling method. The influence of different rolling characteristics was discussed, and the dynamic scaling deviation was subsequently evaluated.

2. SCALING METHOD UNDER ROLLING CONDITIONS

Several motions of ships and other floating devices in the ocean are shown in Figure 1a [Figure 1: see original paper]. In this study, the rolling motion among them was analyzed. For convenience of analysis, an LBE natural circulation rectangular loop model was built as shown in Figure 1b.

It is assumed that the flow area in the loop remains uniform, and the Boussinesq hypothesis [?] is applied to the LBE fluid. Additionally, it is considered that the loop has good thermal insulation performance except for the heating and cooling sections [?, ?]. Moreover, the specific numerical model will be introduced in Section 3.1.

The mass conservation equation of the LBE natural circulation can be expressed as:

$$\rho u_i A_i = \rho u_0 A_0$$

Subscript i denotes any position in the loop, and 0 denotes the reference value. Similarly, the momentum conservation equation under rolling condition is as follows:

$$\left[\sum\left(\frac{A_0}{A_i}\right)\right]=\beta_s a_M \rho(T_h-T_c)H-\left[\sum\left(\frac{A_0}{A_i}\right)\left(\frac{fL}{D}\right)\right]$$

Herein, a_M denotes the corrected acceleration under dynamic conditions. For rolling conditions, we have:

$$a_M=g+a_c+a_t$$

a_c and a_t denote the centripetal acceleration and tangential acceleration respectively during rolling motion. They give:

$$a_c=\omega^2 r$$

$$a_t=\varepsilon r$$

In this study, the rolling case was simplified to sinusoidal excitation and the variation of the rolling angle with time can be expressed as [**?**]:

$$\theta(t)=\theta_{\max}\sin\left(\frac{2\pi}{T_M}t\right)$$

$\theta_{\max}$ represents the rolling amplitude while T_M represents the rolling period. Then, the angular velocity and angular acceleration can be expressed respectively as:

$$\omega(t)=\dot{\theta}=\theta_{\max}\left(\frac{2\pi}{T_M}\right)\cos\left(\frac{2\pi}{T_M}t\right)$$

$$\varepsilon(t)=\ddot{\theta}=-\theta_{\max}\left(\frac{2\pi}{T_M}\right)^2\sin\left(\frac{2\pi}{T_M}t\right)$$

We defined the dimensionless parameters: $u^+=u/u_0$, $t^+=t/t_0$ and $\Delta T^+=\Delta T/\Delta T_0$. Thus, Eq. (2) can be expressed as:

$$\frac{du^+}{dt^+}=\frac{\beta_s a_M H\Delta T_0}{u_0^2}\Delta T^+-\left(\frac{fL}{D}\right)(u^+)^2$$

To ensure similarity between the scaled-down and prototype loops, the following criteria can be derived from the continuity and momentum equations:

Flow area criterion:

$$\Pi_{A,R} = \left[\left(\frac{A_0}{A_i}\right)\left(\frac{\rho_0}{\rho_i}\right)\right] = 1$$

Richardson number criterion:

$$\Pi_{Ri,R} = \left(\frac{\beta_s g H \Delta T_0}{u_0^2}\right)_R = 1$$

Friction number criterion:

$$\Pi_{Fri,R} = \left(\frac{fL}{D}\right)_R = 1$$

Where the friction loss coefficient can be expressed as $f = \frac{64}{\mathrm{Re}^{1/4}}$ [**?**].

Rolling acceleration criterion:

$$\Pi_{a,R} = 1$$

Eq. (13) can be described in detail as follows:

Rolling amplitude criterion:

$$\theta_{\max,R} = 1$$

Centripetal acceleration and tangential acceleration criterion:

$$\left(\frac{a_c}{g}\right)_R = \left(\frac{\omega^2 r}{g}\right)_R = 1, \quad \left(\frac{a_t}{g}\right)_R = \left(\frac{\varepsilon r}{g}\right)_R = 1$$

Where $\omega = \dot{\theta}$ and $\varepsilon = \ddot{\theta} = \theta\left(\frac{2\pi}{T_M}\right)^2$.

Then, the local phenomena of natural circulation are discussed. The energy balance equation for the heating section is:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u \frac{\partial T}{\partial z} = \frac{4q}{d}$$

By defining $z^+ = z/l_0$, Eq. (17) can be written as:

$$\frac{\partial T^+}{\partial t^+} + \frac{\partial T^+}{\partial z^+} = \frac{4ql_0}{\rho C_P d u_0 \Delta T_0}$$

The heat source number criterion can be given:

$$\Pi_{Qs,R} = \left(\frac{4ql_0}{\rho C_P d u_0 \Delta T_0} \right)_R = 1$$

The same analysis is applied to the cooling section and the Stanton number is obtained.

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u \frac{\partial T}{\partial z} = -\frac{4k_s}{d\delta_0}(T - T_c)$$

$$\Pi_{st,R} = \left(\frac{4Lk_s}{\rho C_P d u_0 \delta_0} \right)_R = 1$$

Finally, the similarity criteria of LBE natural circulation under rolling condition can be summarized as follows:

$$\theta_{\max,R} = 1, \quad T_{M,R} = L_R^{1/2}, \quad u_R = L_R^{1/2}, \quad q_R = L_R^{1/5}, \quad d_R = L_R^{7/10}, \quad \delta_R = L_R^{-1/5}, \quad \Delta T_R = 1$$

3.1. CFD Model and Boundary Conditions

The prototype LBE loop shown in Fig. 2a [Figure 2: see original paper] was investigated using Fluent. The simple rectangular loop is composed of a heat source, a heat exchanger, and adiabatic pipe sections. The rotating axis of the rolling motion was set at the midpoint of the bottom horizontal pipe. The specific design parameters of the rolling loop are presented in Table 1 . Moreover, sensitivity analysis of the grid was performed to investigate the effects of grid number on LBE flow rate and temperature difference between hot and cold sections in the loop. As shown in Fig. 2b, when the number of grids is around one million, the circulation parameters tend to stabilize. To obtain a balance between computational accuracy and time, the number of grids was set at 1×10^6.

In the model, a constant heat flux boundary condition is used for the heat source section, while a wall temperature boundary condition is used for the cooling section. Density variations resulting from temperature difference drive LBE natural circulation. The thermal properties of liquid lead-bismuth are provided in Table 2 [?]. In recent studies, Reference [?] compared common turbulence models to analyze their influence on LBE flow and heat transfer characteristics. The results showed that predictions of the SST k-omega model are in good agreement with experimental correlations, especially in the low flow rate region corresponding to natural circulation. Therefore, the SST k-omega model was adopted in this study.

3.2. Validation of Computational Method

Currently, Fluent does not include computational models for marine conditions. Thus, after establishing the lead-bismuth natural circulation model, it is necessary to use User-Defined Function (UDF) to add the model of additional force for simulating rolling motion into the source term. The reliability of the prototype loop and rolling UDF code was verified by comparing results from two studies: one by Li et al. [?] from the University of Science and Technology of China, based on the KYLIN-II natural circulation loop, and the other by Yuan et al. [?] from Xi' an Jiaotong University, based on the LECO facility. Figures 3a and 3b respectively show schematic diagrams of the two experimental facilities.

Static circulation model validation. The KYLIN-II natural circulation loop is structurally similar to the present model but differs in geometric parameters. The same modeling method was applied to simulate the KYLIN-II loop, and results were compared with previous research [?] to verify the reliability of the modeling methodology.

Steady conditions of natural circulation were calculated. By varying the power of the heating section, multiple sets of corresponding data on temperature difference and mass flow rate were obtained. A comparison of calculated values from the reference, experimental data [?], and simulation results is presented in Fig. 4 [Figure 4: see original paper]. It can be seen that simulation results are very close to calculated results from previous research, and both sets of results follow the same trend as experimental data.

Calculated values of flow rate and temperature difference show good agreement with experimental results at high input powers. However, when power is below 5 kW, the calculated mass flow rate is higher than the experimental value, while the temperature difference is lower. This is mainly due to relatively significant heat dissipation of the experimental loop at low input power [?]. The results show that the numerical model method for LBE natural circulation loop is reasonable.

Rolling code validation. Then, the UDF code of rolling additional force is verified by comparing with Xi' an Jiaotong University' s research [?]. As shown in Fig. 4b, the LECO loop differs from the loop used in this study only in the location of the cooling section and pipe diameter of the heating section (test section). Since these differences are minor, the comparison remains relevant. It should be noted that there is an electromagnetic pump in the LECO loop; however, validation was only based on results of natural circulation. The experimental and preheating sections were subjected to heat flux boundary conditions, while a constant wall temperature boundary condition was applied to the cooling section. The remaining parts of the loop were regarded as adiabatic.

Dynamic and time-averaged values of LBE flow rate were calculated. As shown in Fig. 5a-d, the UDF code was validated by comparing simulation results with reference data. It can be seen that curves of dynamic and time-averaged values of mass flow rate are both in good agreement with the previous study [**?**] at varying amplitudes and periods.

In summary, the LBE natural circulation rolling model developed in this study is valuable for further analysis according to the verification presented in Sections 3.2.

3.3. Dynamic Motion Cases of Prototype Circulation

To comprehensively analyze the impact of rolling period and amplitude characteristics on the scaling method, four rolling motion processes as shown in Table 3 were set up. For the prototype LBE circulation loop, the rolling angles were 20° and 10°, and the rolling periods were 12 s and 8 s respectively. Curves of flow rate variations with time under steady-state and motion conditions in the prototype loop were calculated separately, with results shown in Fig. 6 [Figure 6: see original paper].

It can be seen that LBE natural circulation exhibits regular periodic fluctuations under sinusoidal rolling excitation. It should be noted that the cycles presented in Fig. 6 are the several cycles after rolling motion stabilized. The amplitude of flow rate fluctuation increases with increasing rolling amplitude and decreasing rolling period. This is consistent with conclusions of previous research [**?**, **?**]. Furthermore, backflow of LBE occurred in the loop when fluctuation was large, indicating that rolling conditions have a significant impact on natural circulation stability.

The scaling criteria of scaled-down models are presented in Table 4 . Steady state and time-averaged deviations of natural circulation flow rate and temperature difference between hot and cold sections for scaled-down models are shown in Table 5 . Flow rates and temperature differences of LBE corresponding to all scaled-down cases are consistent with theoretical values, with a maximum deviation of 9.08%. This shows that criteria based on the above scaling method can reflect time-averaged characteristics of the prototype natural circulation loop.

Then, dynamic scaling distortions under rolling processes were discussed. To better compare circulation characteristics under different cases, parameters of the scaled-down loop were normalized and the dimensionless curve of LBE mass flow rate was obtained. The vertical ordinate is defined as follows:

$$W^* = \frac{W - W_1}{W_2 - W_1}$$

Where W represents transient flow rate variation and W_1 and W_2 represent maximum and minimum values during rolling processes, respectively. Moreover, to compare the relationship of circulation characteristics between scaled-down cases and prototype within each period more clearly, the horizontal ordinate is defined as follows:

$$t^* = \frac{t}{t_0}$$

Where t_0 is the time required for LBE to complete a cycle in the loop, which depends on time-averaged flow rate and total length of the loop. To eliminate overall distortion caused by accumulation of time-averaged flow rate errors, the dimensionless time correction factor is defined as $e_t = u_t/u_{R,T}$. Where u_R and $u_{R,T}$ represent the ratio of time-averaged flow velocity between scaled-down cases and prototype cases, and the ratio of theoretical flow velocity, respectively.

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4. RESULTS AND DISCUSSION

The scaling method was applied to rolling processes of the prototype loop established in Section 3.3. Two common scaled-down cases with length ratios $L_R = 0.5$ and $L_R = 0.25$ were selected to evaluate scaling distortion.

Figs. 7a-d show normalized flow rate curves of prototype and scaled-down cases under different rolling processes. The dimensionless time range of one circulation cycle was selected for analysis. It is noted that all curves are around 0.5 at the start of dynamic processes, indicating that transient values of flow rate at this moment are close to time-averaged values throughout the whole cycle, and all cases start a new circulation cycle simultaneously. Normalized flow rates of all prototypes and scaled-down models exhibit standard sinusoidal fluctuations, which correspond to applied rolling additional force. Meanwhile, curves corresponding to different length ratios are almost identical and highly consistent with prototype within each period. These results demonstrate that the scaling method can accurately simulate fluctuation characteristics of flow rate under rolling processes.

Figure 8 shows normalized curves of temperature difference which is defined as $\Delta T^* = \frac{\Delta T - \Delta T_1}{\Delta T_2 - \Delta T_1}$, where ΔT_1 and ΔT_2 are maximum and minimum temperature differences between hot and cold sections. Obviously, temperature difference of the loop does not follow ideal sinusoidal periodic fluctuations. The curves exhibit different fluctuations with changes in rolling amplitude and period. As shown in Figs. 8a and 8b, temperature difference exhibits significant fluctuations around the minimum value within the period. The curve rapidly reaches the minimum value and subsequently increases by approximately 0.3. Then, the curve gradually decreases until it reaches the next period. Comparing Figs. 8a and 8c with Figs. 8b and 8d, as rolling amplitude decreases, oscillations of temperature difference become increasingly slight, and curves gradually approach sinusoidal shape.

Differences between scaled-down models and prototypes have been compared. In general, scaled-down models agree with dynamic characteristics of temperature difference of prototypes under all motion processes. However, scaling cases of temperature differences show some deviations, which are different from those of flow rate. As shown in Fig. 8a, temperature difference curves of the two scaled-down cases both exhibit hysteresis compared with prototype. This is not obvious in the process where dimensionless curves decrease from their maximum value, but it is more significant in oscillating and rising phases. Comparison with Fig. 8b shows that hysteresis of curves gradually diminishes as rolling period decreases. The same conclusion can be obtained by comparing Figs. 8c and 8d. In addition, influence of length ratios on scaling deviations is not significant.

Figures 9-11 show corresponding dynamic relative scaling errors, with Fig. 9 illustrating errors of normalized mass flow rate and Figs. 10-11 illustrating errors of normalized temperature difference. The ordinate is calculated as $(X_T - X)/X \times 100\%$, where X represents any parameter, and subscript T represents theoretical values. Fig. 9 presents results under fixed rolling processes, comparing cases with different length ratios. Although normalized flow rate curves are consistent, scaled-down cases under different rolling conditions show significantly different dynamic deviations. Curves in Figs. 9a and 9b show such a process within one motion period. Deviations first maintain a low level for relatively long time, then increase suddenly, and subsequently enter a short transitional stage. Following this, deviations fluctuate again momentarily and eventually enter a new period. Scaling deviations are within ±10% and ±20% for most of time within one period, with dashed lines marking this range clearly. This indicates good agreement between scaled-down models and prototypes for most of the time. The conclusion is similar to that for dimensionless curve. However, flow rate shows significant distortion during some brief moments, and density of data points confirms this. It can be easily explained from Fig. 6 that backflow can be observed in rolling processes 1 and 2. Flow rate shows two extremely low regions near zero during its "forward-backward-forward" circulation within a rolling period. Low flow rate in prototype loop causes transient distortion since scaled-down cases cannot accurately and synchronously reflect moments of extremely low flow rates.

In addition, backward flow rate in process 1 remains consistently small throughout the period. Consequently, errors observed in region between two distortion peaks are larger for scaled-down cases of process 1 than for those of process 2. Processes 3 and 4 exhibit distinct error curves, as shown in Figs. 9c and 9d. Deviations in Process 3 are smaller than those in Process 4 because its flow rate fluctuations are slight relative to time-averaged value. Furthermore, curves only exhibit unidirectional fluctuations, as natural circulation in these processes did not experience backflow.

In summary, periodic distortion in flow rate of scaled-down model is due to low flow rate regions during rolling motion. Backflow is a characteristic of rolling motion and may cause instability within circulation [?]. When natural circulation during motion processes exhibits backflow, scaling deviations during fluctuation show no obvious relationship with individual parameters such as rolling amplitude and rolling period. Excluding brief periods of fluctuation, there is good agreement between models with different length ratios and prototype in all rolling processes.

Fig. 10 shows results with fixed rolling process, comparing scaled-down cases corresponding to temperature difference between hot and cold sections, while Fig. 11 shows results under different rolling processes for a given length ratio. Overall, temperature difference distortion exhibits different profiles from those of mass flow rate distortion and shows no significant deviations. In Fig. 10a, transient error of temperature difference in rolling process 1 is slightly larger. As shown in Fig. 8a, distortion is attributed to hysteresis of scaled-down curves and their sustained fluctuations within range of low temperature difference. Correspondingly, dynamic distortion of rolling processes 2-4 is relatively small. Results are consistent with previous analysis of Fig. 8. Moreover, similar to analysis of steady cases, Fig. 10 shows that length ratio has no significant influence on dynamic deviations. As shown in Fig. 11, for a given length ratio, temperature errors of LBE natural circulation decrease with decreasing rolling amplitude and rolling period.

Based on time-averaged parameters, transient errors of similarity criterion numbers for various scaled-down cases are listed in Table 6 . For convenience of comparison, distortion analysis for Friction number is neglected here since the criterion can be easily satisfied by adjusting loop resistance coefficient in experimental facilities [**?**]. Deviation of Richardson number is within ±18.56%, while deviations of heat source number and Stanton number are less than ±9.78%. Deviation of Richardson number is slightly larger, which can be revealed from analysis of multiple groups of independent variables. Generally, it is clear that the method is applicable to scaling analysis of marine rolling motion.

Transient Richardson number distortion, in which steady and time-averaged values are substituted by transient parameters, was calculated for comprehensive comparison, as shown in Fig. 12 a-d. Relative error shows periodic fluctuations with rolling motion, and in Process 1, errors of approximately 150% occur at brief moments. It is easy to understand from Eq. (11) that error sources of Richardson number are scaling distortion of flow rate and temperature difference. Periodic distortion caused by flow instability also induces dynamic errors of criterion numbers. The same analysis was conducted for other criterion numbers, and similar conclusions were obtained. Corresponding figures have been omitted due to space limitations.

5. CONCLUSIONS

To study dynamic natural circulation of LBE under marine rolling conditions, a scaling analysis method was established and an array of similarity criteria was derived. Models were simulated with Fluent code under different rolling processes. Dynamic scaling distortion for natural circulation parameters was calculated and rationality of the scaling method was evaluated. The following conclusions were drawn:

(1) Rolling motion exerts additional forces on circulation flow. A scaling analysis method for dynamic rolling process of LBE natural circulation was established by introducing acceleration criterion. Scaled-down models can be used to effectively simulate periodic processes of the prototype. Time-averaged values of LBE flow rate and temperature difference are accurately reproduced, and errors are all within ±9.08%. Furthermore, length ratio has no significant effect on scaling deviation.

(2) The phenomenon of backflow may be induced by rolling motion and causes flow rate to be in an extremely low range at certain moments. This leads to periodic and instantaneous scaling distortion. Transient deviation of flow rate is determined by specific motion processes when there is backflow in the rolling loop, and its correlation with any individual parameter is not obvious. There is good agreement between model and prototype in all rolling processes excluding brief periods of oscillation.

(3) Temperature difference between hot and cold sections of natural circulation does not follow ideal sinusoidal fluctuations. Instead, it produces irregular fluctuations as it varies with rolling parameters. Despite slight hysteresis, scaled-down models reflect fluctuations of the prototype accurately. When length ratio is fixed, temperature difference errors of LBE natural circulation decrease with decreasing rolling amplitude and rolling period.

(4) Relative deviations of Richardson number, Stanton number, and heat source number calculated from time-averaged system parameters are within an acceptable range. Moreover, their dynamic errors show periodic fluctuations with rolling motion, which correspond to distortion of circulation characteristics.

In this study, only rolling condition of marine motion is analyzed. For future work, other types of marine motions will be further considered and uniform similarity criteria of complex dynamic processes will be comprehensively evaluated.

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Note: Figure translations are in progress. See original paper for figures.