

Analysis of Six-Degree-of-Freedom Motion Effects on Sodium Pool Behavior in a Marine SFR Reactor Vessel Using AMESim

Seon-Gon Kim^a, Sang-bum Son^a, Jae-Ho Jeong^{a*}

^aDepartment of Mechanical Engineering, Chung-Ang University, Seoul 06974, Republic of Korea

*Corresponding author: jaehojeong@cau.ac.kr

***Keywords :** Sodium-cooled Fast Reactor, Six-Degree-of-Freedom Motion, Marine Nuclear System, AMESim, Reactor Vessel

1. Introduction

Marine nuclear power systems are subjected to continuous platform motions induced by ocean environments, and these motions can introduce additional inertial effects that influence the thermal-hydraulic behavior of reactor coolant systems [1,2]. Previous studies have developed moving-reactor models for conventional system thermal-hydraulic codes, particularly MARS-KS, to account for the effects of platform motion on pressure head and fluid momentum [1,2]. In contrast, published applications of MARS-LMR, which was developed for sodium-cooled fast reactor (SFR) safety analysis, have mainly focused on the thermal-hydraulic behavior and transient safety analysis of SFR systems, including the PGSFR and related experimental facilities [3-5]. For marine nuclear propulsion applications, however, an integrated system-level modeling environment capable of coupling reactor thermal-hydraulics with power-conversion, electrical, control, and ship-propulsion systems is also required. Simcenter AMESim provides a multi-domain system simulation environment suitable for such integrated modeling, and its applicability to PGSFR thermal-hydraulic system analysis has been investigated in previous studies [6,7].

In this study, a six-degree-of-freedom (6DOF) motion analysis model for a sodium-cooled reactor vessel was developed using Simcenter AMESim 2022.1. A 100MWt-equivalent reactor vessel model was scaled from the PGSFR reference design based on Ishii's three-level scaling framework adopted in the design of the STELLA-2 integral-effect test facility [4,5]. Under geometric similarity, the characteristic length scale of the reactor vessel was determined using the power scaling relationship of the similarity methodology, and the scaled reactor vessel geometry was subsequently implemented in AMESim. The reactor vessel was modeled using the Variable Orientation and Acceleration Tank model in the Aircraft Fuel System library, with liquid sodium as the coolant and argon as the cover gas. Six-degree-of-freedom ship-motion histories obtained from STAR-CCM+ marine-motion simulations were applied to the AMESim reactor-vessel model to investigate the effects of marine motion on the sodium pool. The responses of the liquid center of gravity, liquid-gas interface characteristics, cover-gas pressure, and

liquid pressure were selected as the major response parameters.

2. Analysis Methodology

The analysis methodology consists of three main steps: scaling of the PGSFR reference reactor to establish a 100MWt-equivalent reactor vessel, development of the reactor vessel model using Simcenter AMESim, and application of six-degree-of-freedom (6DOF) marine motion to the developed model.

2.1 Scaling Methodology for the 100MWt Reactor Vessel

The PGSFR was selected as the reference reactor, and the reactor vessel was scaled to a 100MWt-equivalent model based on Ishii's three-level scaling framework adopted for the STELLA-2 design [4,5]. The STELLA-2 methodology defines the power scale as $a_R \sqrt{l_R}$, where a_R and l_R denote the area and characteristic length scale ratios, respectively.

$$Q_R = a_R \sqrt{l_R}$$

Under geometric similarity,

$$a_R = l_R^2$$

and therefore,

$$Q_R = l_R^{5/2}$$

For the target thermal power of 100MWt relative to the 392.2MWt PGSFR, the characteristic length scale was determined as

$$l_R = \left(\frac{100}{392.2}\right)^{2/5} = 0.5789$$

The resulting scale ratios and reactor vessel dimensions are summarized in Table 1.

Table 1: Scaling parameters and dimensions of the 10 MWt-equivalent reactor vessel

Parameter	PGSFR	100MWt Model
Thermal power [MWt]	392.2	100
Length scale, (l_R)	1.00	0.5789
Area scale, (a_R)	1.00	0.3351
Volume scale, (V_R)	1.00	0.1940
Inner diameter [m]	10.422	6.033
Inner radius [m]	5.211	3.306
Outer diameter [m]	10.522	6.091
RV height [m]	15.574	9.881

2.2 AMESim Reactor Vessel Modeling

The scaled reactor vessel was modeled using Simcenter AMESim 2022.1. The Variable Orientation and Acceleration Tank model in the Aircraft Fuel System library was employed to represent the sodium pool subjected to marine motion. A cylindrical reactor vessel was generated using the dimensions in Table 1, and CAD-based tank mapping was performed for roll and pitch variations. The mapping ranges were set to -30° to $+30^\circ$ for roll and -15° to $+15^\circ$ for pitch with a 5° interval.

Liquid sodium and argon were applied as the reactor coolant and cover gas, respectively. The initial temperatures of both fluids were set to 545°C , the initial cover-gas pressure was 1.013 barA, and the sodium filling ratio was approximately 80%. The reactor vessel was modeled as a closed tank to evaluate the response of the sodium pool to the imposed motion.

2.3 Governing Relations for Six-Degree-of-Freedom Motion

The six-degree-of-freedom motion of the reactor vessel was represented using the rigid-body motion formulation implemented in the Aircraft Fuel System library. The vessel attitude was calculated using the Tait-Bryan yaw-pitch-roll coordinate transformation as

$$R = R_\psi R_\theta R_\phi$$

The acceleration at an arbitrary position in the reactor vessel was calculated by considering translational, centrifugal, and Euler acceleration components:

$$a_{AC}(M) = a_{AC}(C) + \omega * (\omega * r_{CM}) + \dot{\omega} * r_{CM}$$

The effective acceleration acting on the liquid sodium was then calculated as

$$a_f(M) = g - a_{AC}(M)$$

Based on effective acceleration, the liquid free-surface orientation and CAD-based tank-map parameters were determined. The liquid pressure was calculated using the hydrostatic pressure relation:

$$P_{liq}(M) = P_{gas} + \rho_{liq} \|a_f(M)\| h_{fl}$$

Six-degree-of-freedom (6DOF) ship-motion data were obtained from STAR-CCM+ simulations and applied to the AMESim reactor vessel model. The motion inputs consisted of roll, pitch, and yaw angles together with three-axis linear accelerations corresponding to the surge, sway, and heave motions.

3. Results and Discussion

3.1 Verification of the AMESim Reactor Vessel Model

The developed reactor vessel model was evaluated under static and roll-motion conditions to verify the consistency of the CAD-based tank mapping. Under the static closed-tank condition, the liquid sodium volume and mass remained constant, while the argon cover-gas pressure was maintained at approximately 1.013 barA. The calculated vertical position of the liquid center of gravity was approximately 3.95 m, which was consistent

with the theoretical centroid of the 80%-filled cylindrical liquid volume.

For the cylindrical reactor vessel with a radius of 3.306 m, the theoretical liquid-gas interface area under the static condition was calculated as 34.336 m^2 , which agreed with the AMESim result of approximately 34.34 m^2 . Under a roll angle of 15° , the analytical free-surface area was calculated as

$$A(\theta) = \frac{\pi R^2}{\cos(\theta)}$$

resulting in an interface area of 35.548 m^2 . The corresponding AMESim result was approximately 35.5 m^2 , giving a relative deviation of approximately 0.13%. The liquid COG also varied continuously with the imposed roll motion. These results confirm that the CAD-based tank mapping adequately represents the global redistribution of the sodium pool caused by vessel inclination.

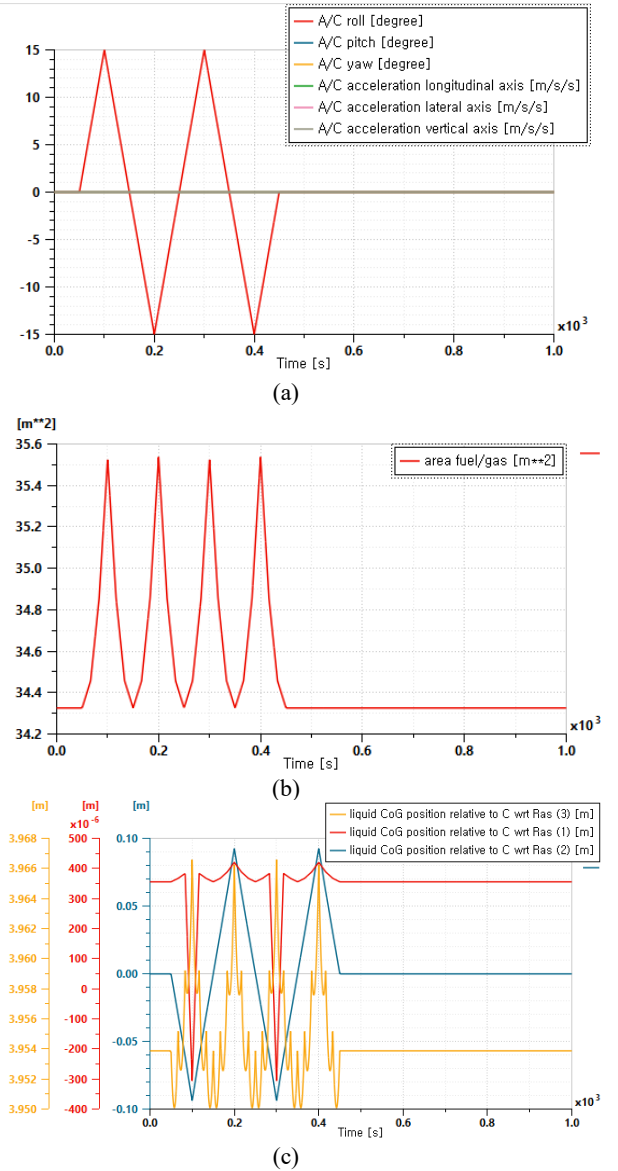


Fig. 1. Verification of sodium-pool response under roll motion: (a) roll-angle input, (b) liquid-gas interface area, and (c) liquid center-of-gravity response.

3.2 Sodium Pool Response under 6DOF Motion

The six-degree-of-freedom motion data obtained from the STAR-CCM+ ship-motion analysis were applied to the verified AMESim reactor vessel model. The imposed motion consisted of roll, pitch, and yaw angles together with three-axis linear accelerations corresponding to surge, sway, and heave motions.

Under the Pacific Ocean motion condition, the liquid center of gravity continuously responded to the imposed 6DOF motion. The horizontal COG displacement remained within approximately ± 0.02 – 0.03 m, while the vertical COG fluctuated within a limited range around 3.95 m. These results indicate continuous but bounded redistribution of the sodium pool under the applied marine-motion condition.

The liquid-gas interface area varied from approximately 34.34 m^2 to 34.52 m^2 , corresponding to a maximum increase of approximately 0.18 m^2 , or about 0.52%, relative to the static interface area. The sodium mass and liquid volume remained constant throughout the transient, and the argon cover-gas pressure was maintained at approximately 1.013 barA. These results demonstrate that the applied 6DOF marine motion produces measurable variations in the liquid COG and free-surface characteristics while maintaining the overall inventory of the closed reactor vessel.

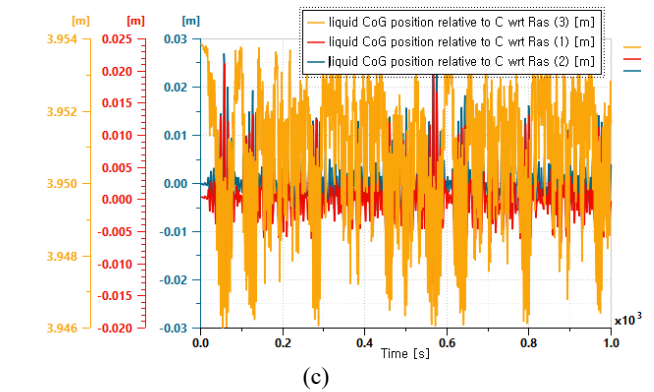
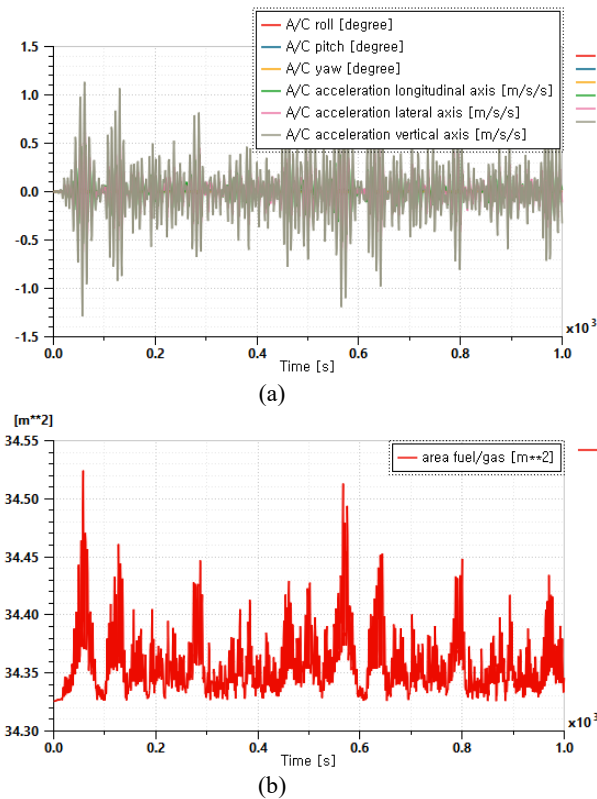


Fig. 2. Sodium-pool response under Pacific Ocean 6DOF motion conditions: (a) imposed 6DOF motion histories, (b) liquid-gas interface area, and (c) liquid center-of-gravity response.

4. Conclusions

A 100 MWt-equivalent marine SFR reactor vessel model was developed based on the PGSFR reference design using Ishii's three-level scaling framework. The scaled reactor vessel was implemented in Simcenter AMESim 2022.1 using the Variable Orientation and Acceleration Tank model, with liquid sodium and argon applied as the coolant and cover gas, respectively.

The developed model was evaluated using six-degree-of-freedom marine motion data obtained from STAR-CCM+ simulations. The results showed that the liquid center of gravity and liquid-gas interface area varied continuously with the imposed ship motion, while the sodium mass and volume remained conserved. These results demonstrate the applicability of AMESim for evaluating the global sodium-pool response of an SFR reactor vessel under 6DOF marine motion at the system level.

The developed reactor vessel model provides a basis for further integration with the reactor core, primary pump, and intermediate heat exchanger, and ultimately for the development of an integrated marine nuclear system model including electrical and ship-propulsion systems.

ACKNOWLEDGMENTS

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Ministry of Climate, Energy and Environment (MCEE) (No.RS-2024-00401705).

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (RS-2025-02311287)

REFERENCES

- [1] H. K. Beom, G. W. Kim, G. C. Park, and H. K. Cho, Verification and Improvement of Dynamic Motion Model in MARS for Marine Reactor Thermal-Hydraulic Analysis under Ocean Condition, Nuclear Engineering and Technology, Vol. 51, pp. 1231-1240, 2019.
- [2] H. Seo, M. H. Choi, S. W. Park, G. W. Kim, H. K. Cho, and B. D. Chung, Moving Reactor Model for the MULTID Components of the System Thermal-Hydraulic Analysis Code MARS-KS, Nuclear Engineering and Technology, Vol. 54, pp. 4373-4391, 2022.
- [3] J. Yoo, J. Chang, J. Y. Lim, J. S. Cheon, T. H. Lee, S. K. Kim, K. L. Lee, and H. K. Joo, Overall System Description and Safety Characteristics of Prototype Gen IV Sodium Cooled Fast Reactor in Korea, Nuclear Engineering and Technology, Vol. 48, pp. 1059-1070, 2016.
- [4] J. Lee, J. Eoh, J. Yoon, S. K. Son, and H. Kim, Design of Large-Scale Sodium Thermal-Hydraulic Integral Effect Test Facility, STELLA-2, Nuclear Engineering and Technology, Vol. 54, pp. 3551-3566, 2022.
- [5] J. Lee, J. Eoh, H. Kim, J. Yoon, Y. B. Lee, E. K. Kim, J. H. Jeong, K. L. Lee, and J. Y. Jeong, Design Evaluation of Large-Scale Sodium Integral Effect Test Facility (STELLA-2) Using MARS-LMR, Annals of Nuclear Energy, Vol. 120, pp. 845-856, 2018.
- [6] S. G. Kim and J. H. Jeong, Development of AMESIM Code Based Safety Analysis Methodology for PGSFR, Proceedings of Advances in Thermal Hydraulics (ATH 2024), pp. 712-721, 2024.
- [7] S. G. Kim, B. G. Paik, and J. H. Jeong, Development of an Innovative Safety Analysis Framework Based on AMESIM for SFR, Proceedings of the KSFM 2025 Summer Annual Meeting, 2025.