

Transient Drainage Performance of a Marine Molten Salt Reactor under Rolling Motion

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1. Introduction

Marine molten salt reactors (MSRs) have attracted increasing attention for shipboard and offshore power generation because of their compact configuration and inherent safety characteristics [1,2]. A key safety feature of liquid-fueled MSRs is the gravity-driven emergency drain system, which transfers fuel salt from the active fuel system to a geometrically subcritical and passively cooled drain tank. Because the process relies primarily on gravitational head, complete and timely fuel transfer is essential to the effectiveness of this passive safety function.

In marine environments, rolling periodically changes the effective gravity direction and introduces additional inertial forces, modifying the hydraulic head, free-surface response, and drain-line flow. A previous air-water surrogate study showed that rolling can induce periodic discharge oscillations and increase residual liquid hold-up [3]. However, the drainage performance under full-scale molten-salt conditions and its dependence on both rolling amplitude and period remain insufficiently quantified.

In this study, the emergency drain behavior of the full-scale MARINA configuration is investigated using VOF-based CFD with NaCl–KCl–UCl₃ fuel salt and helium [4]. Stationary and rolling conditions are compared over an identical 300 s drain transient. The effect of rolling is evaluated using the residual LFS fuel inventory, molten-salt mass flow rate, and drain-line liquid volume fraction to assess both the overall drainage performance and the hydraulic mechanism responsible for its degradation.

2. Methods

The computational domain consists of an equivalent liquid fuel system (LFS) tank, inclined drain line, siphon pot, freeze-valve section, and drain tank, as shown in Fig. 1. The LFS diameter and initial fuel level are 2.101 m and 3.6 m, respectively, while the drain-pipe diameter is 0.12225 m.

Transient calculations were performed using ANSYS Fluent 2025 R2 with the VOF model and $k-\omega$ SST turbulence model. A 679,097-cell polyhedral mesh was adopted based on the mesh-independence assessment. The working fluids were NaCl–KCl–UCl₃ fuel salt

($\rho=3331 \text{ kg/m}^3$, $\mu=2.78 \times 10^{-3} \text{ Pa}\cdot\text{s}$) and helium at 605 °C and 3 bar.

Rolling was imposed in a fixed computational frame through a user-defined function that updates the gravity vector and the centrifugal, Euler, and Coriolis source terms. Two rolling amplitudes, 20° and 30°, and two rolling periods, 10 s and 20 s, were considered. Accordingly, four rolling conditions, 20°–10 s, 20°–20 s, 30°–10 s, and 30°–20 s, were analyzed together with a stationary reference case. All cases were evaluated over an identical 300 s drainage transient.

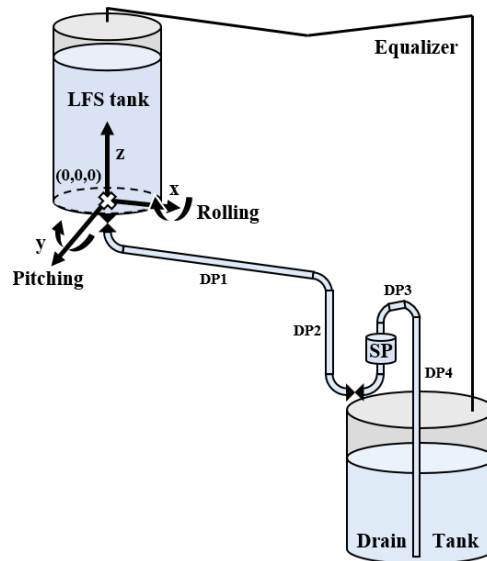


Fig. 1. Computational domain of the MARINA emergency drain system.

3. Results

Fig. 2 compares the transient fuel inventory in the LFS under the stationary condition and the four rolling conditions. Rolling delayed fuel drainage relative to the stationary case for all combinations of amplitude and period. The stationary case approached complete drainage within the 300 s simulation, whereas all rolling cases retained a larger amount of fuel salt in the LFS.

Within the rolling cases, a systematic dependence on the imposed amplitude and period was observed. At the same rolling period, increasing the rolling amplitude from 20° to 30° resulted in faster drainage. This tendency

was observed for both the 10 s and 20 s periods. Similarly, at the same rolling amplitude, the 10 s period resulted in faster drainage than the 20 s period for both the 20° and 30° cases. Thus, within the investigated range, the drainage response was influenced by both rolling amplitude and period. Nevertheless, even the relatively faster rolling cases drained more slowly than the stationary case, indicating that the presence of rolling itself degraded the overall gravity-driven drainage performance.

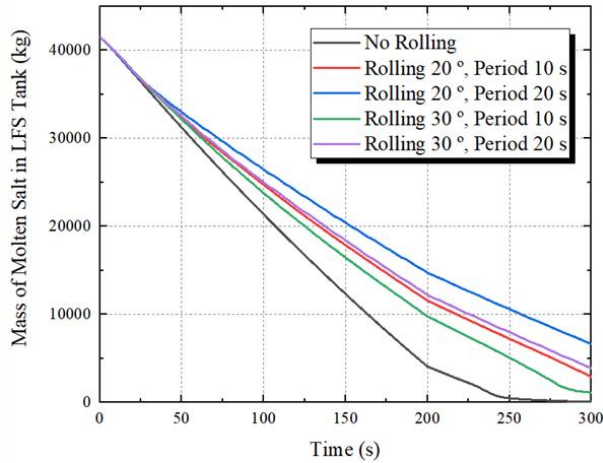


Fig. 2. Transient molten-salt inventory in the LFS under stationary and rolling conditions.

The difference between the rolling cases also demonstrates that drainage degradation cannot be characterized simply by the magnitude of the roll angle. Although a larger inclination periodically reduces the gravity component acting in the nominal drain direction, the rolling motion simultaneously introduces time-dependent inertial effects and continuously redistributes the liquid within the LFS. Consequently, the cumulative drainage response depends on the transient hydraulic behavior throughout the rolling cycle rather than on the instantaneous roll angle alone.

To determine whether the drainage degradation was associated with the onset of gas-liquid flow, the area-averaged liquid volume fraction was evaluated at the drain pipe immediately downstream of the freeze valve. In the stationary case, the drain line remained predominantly liquid-filled during most of the transient. As the LFS approached depletion, however, the liquid volume fraction decreased below the operational criterion of 0.95 at approximately 226 s and subsequently decreased rapidly to approximately 0.14 at 300 s. This behavior indicates late-stage outlet uncovering and gas ingestion following substantial depletion of the LFS.

In contrast, the rolling cases remained predominantly liquid-filled at the drain pipe monitoring location during the 300 s simulation. Therefore, the increased residual inventory under rolling was established before significant gas ingestion or sustained two-phase flow occurred. The delayed drainage under rolling cannot therefore be attributed primarily to gas ingestion. Instead,

the results indicate that rolling modified the hydraulic response during the liquid-filled drainage stage, delaying LFS depletion and consequently postponing the transition to gas-liquid flow.

4. Conclusions

A VOF-based CFD analysis was performed to evaluate the emergency drainage performance of a marine MSR under rolling motion. A 2×2 matrix consisting of rolling amplitudes of 20° and 30° and periods of 10 s and 20 s was compared with a stationary reference condition over an identical 300 s drainage transient. Rolling delayed the gravity-driven fuel transfer in all investigated cases compared with the stationary condition. Within the rolling cases, increasing the rolling amplitude from 20° to 30° resulted in faster drainage at the same period, while decreasing the rolling period from 20 s to 10 s resulted in faster drainage at the same amplitude. These results indicate that the drainage response is influenced by both rolling amplitude and period and cannot be characterized by rolling angle alone. The drain-line liquid volume fraction showed that the rolling cases remained predominantly liquid-filled during the investigated transient, whereas the stationary case approached LFS depletion and entered a gas-liquid flow regime near the end of the simulation. This suggests that the drainage degradation under rolling was mainly associated with modification of the liquid-filled hydraulic response due to the time-varying effective gravity and additional inertial accelerations, rather than with gas ingestion. The drainage performance under various combined marine motion conditions, including coupled roll and pitch, will be further evaluated to investigate the influence of multi-axis motion on gravity-driven fuel transfer.

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REFERENCES

- [1] M. Drosińska-Komor, J. Głuch, N. Ziółkowska, K. Brzezińska-Gołębiewska, J. Blaut, and P. Ziółkowski, Integrating Fourth-Generation Reactors into Maritime Transport, *Ocean Engineering*, Vol.342, p.122891, 2025.
- [2] S. Park, S. Kim, G. A. K. M. R. Bari, and J.-H. Jeong, Fundamental Understanding of Marine Applications of Molten Salt Reactors: Progress, Case Studies, and Safety, *Journal of Marine Science and Engineering*, Vol.12, p.1835, 2024.
- [3] H. J. Kim and I. C. Bang, Numerical Investigation of a Dual-Tank Drain System under Marine Environment, *Transactions of the Korean Nuclear Society Spring Meeting*, May 7-8, 2026, Jeju, Korea.
- [4] D. Yeo, C. Lee, and G.-H. Koo, Parametric Study of the Fuel Salt Drain System Design of K-MSR, *Transactions of the Korean Nuclear Society Spring Meeting*, 2024.