# Simulation of the K-MSR Fuel Drain System Using MARS and GAMMA+ : Comparison with Scaled Experiments

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## 1. Introduction

The fuel salt drain system is an essential safety feature in molten salt reactors (MSRs), ensuring the transfer of fuel salt to a drain tank under both normal and emergency conditions. The system is designed to rapidly remove fuel salt from the reactor core, preventing recriticality risks while maintaining structural and thermal-hydraulic stability.

To analyze the transient behavior of the K-MSR fuel salt drain system, scaled experimental facility was designed by Korea Atomic Energy Research Institute (KAERI) and Ulsan National Institute of Science and Technology (UNIST). The experimental results were used to validate numerical simulations.

In this study, the drain system's performance was evaluated using both thermal-hydraulics analysis codes MARS-KS and GAMMA+. MARS-KS, widely used for nuclear thermal-hydraulic system analysis, has been extensively validated for various reactor applications. GAMMA+, originally developed for high-temperature gas-cooled reactor (HTGR) simulations, has been extended to include system-level analysis for molten salt reactors. By comparing the predictive capabilities of both codes, this study aims to assess their strengths and limitations in modeling MSR drain system behavior.

## 2. Scaled Experiments

A scaled experimental facility was designed by Korea Atomic Energy Research Institute (KAERI) and Ulsan National Institute of Science and Technology (UNIST) to investigate the fuel salt drain behavior of the K-MSR system. The facility was developed as an approximate 1/4-scale model to replicate key features of the drain system while preserving major flow paths, valve configurations, and overall pressure loss characteristics through appropriate scaling.

The experimental apparatus is consisted of a fuel salt liquid (FSL) tank at the highest point, connected to a drain tank through a network of pipes and valves as shown in Fig. 1. In the process of scaling down the system, water and air were selected as the working fluids, as they were regarded as appropriate for observing the drainage behavior of liquid fuel salt within the given experimental setup. The selection of these working fluids was based on the consideration of the kinematic viscosity ratio and the comprehensive pressure loss coefficient ratio to ensure similarity in drainage characteristics. To maintain similarity in pressure loss characteristics, orifices were installed at both freeze valve simulation sections. Transparent acrylic piping was utilized to enable direct observation of two-phase flow behavior, particularly during the initial and final stages of the drain process. The key components with their dimensions are listed in Table 1.

Fig. 1. K-MSR drain system scaled experimental apparatus

The experiment was conducted under atmospheric conditions, with an initial water level of 80 cm in the FSL tank and an empty drain tank. The drain process was initiated by opening a valve at the bottom of the FSL tank, allowing water to flow through the system into the drain tank. A level transmitter continuously monitored the water level, ensuring accurate measurement of the transient drain behavior, which is a critical aspect of the K-MSR fuel salt drain system.

Table I: Components and dimensions

| Component | Diameter(m) | Length (m) |
|---|---|---|
| FSL Tank | 0.48 | 1.0 |
| DL-1 | 0.032 | 0.031 |
| FV-1 | 0.032 | 0.14 |
| Bend-1 | 0.032 | 0.145 |

| | | |
|---|---|---|
| DL-2 | 0.032 | 1.25 |
| Bend-2 | 0.032 | 0.145 |
| DL-3 | 0.032 | 0.2775 |
| Bend-3 | 0.032 | 0.145 |
| FV-2 | 0.032 | 0.14 |
| Bend-4 | 0.032 | 0.145 |
| Siphon pot | 0.032 | 0.035 |
| | 0.075 | 0.125 |
| | 0.032 | 0.035 |
| Bend-5 | 0.032 | 0.145 |
| DL-4 | 0.032 | 0.3 |
| Bend-6 | 0.032 | 0.145 |
| DL-5 | 0.032 | 1.095 |
| Drain Tank | 0.78 | 0.8 |
| Total height | 1.61 | |
| Total pipe length | 4.3 | |

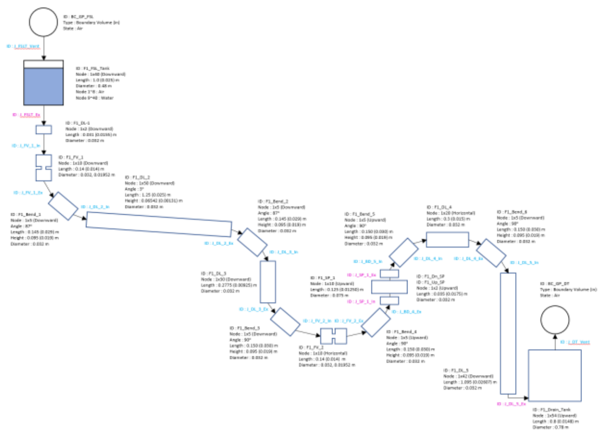

Fig. 2. Nodalization for both MARS and GAMMA+

## 3. Simulation Methods

Numerical simulations were conducted using MARS-KS 2.0 and GAMMA+ and validated by the results of scaled experiments. The computational models were designed to closely replicate the experimental setup, including geometric and boundary conditions.

In order to describe the drain behavior accurately, the most important factor is the pressure loss across the drain pipes. Pressure loss coefficients for each part of the experimental apparatus were computed and are presented in Table II. The derived loss coefficients were used directly in the code input to ensure accurate representation of the system's hydraulic characteristics. These coefficients were applied consistently across both MARS-KS and GAMMA+ simulations to maintain comparability between the two models.

Table II: Used pressure loss coefficient correlation

| Pressure loss coefficient | Correlation |
|---|---|
| Elbow | $\frac{0.0022\theta}{\left(\frac{R_{Bend}}{D}\right)^{0.2}} + \frac{800}{Re}$ |
| Pipe area contraction | $0.5(1 - \frac{A_2}{A_1})$ |
| Pipe area expansion | 1.0 |

For the MARS and GAMMA+ simulation, the experimental apparatus was discretized into 20 components and 304 computational nodes to ensure detailed resolution of the flow dynamics. The FSL tank and Drain tank were modeled as open systems with atmospheric boundary conditions. The two freeze valves were represented by the junction with an opening time of 15 seconds to match the experimental conditions. The detailed nodalization for the codes is shown in Fig. 2.

## 4. Results and Discussion

### *4.1 Water Level in the FSL Tank*

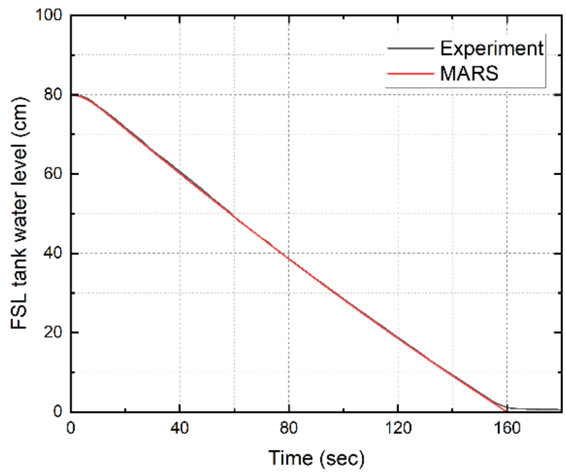


Fig. 3. FSL tank water level through the time (MARS)

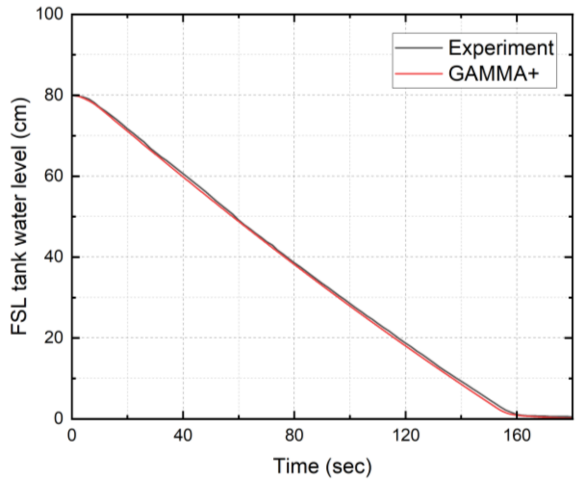


Fig. 4. FSL tank water level through the time (GAMMA+)

The comparison of water level behavior in the FSL tank between the experiment, MARS-KS, and GAMMA+ simulations is presented in Fig. 3 and Fig. 4. The MARS-KS simulation demonstrated strong agreement with the experimental results. GAMMA+ also successfully predicted the transient behavior, accurately capturing the overall drainage trend.

One of the key findings in the result is that GAMMA+ better captured the sudden deceleration of drainage when the water level approached the bottom of the tank, a phenomenon observed in the experiment but not well predicted by MARS-KS. However, despite this strength, the MARS-KS simulation provided a more accurate prediction of residual water levels around the siphon pot and the second freeze valve FV-2.

*4.2 Residual Water Level After the Drainage*

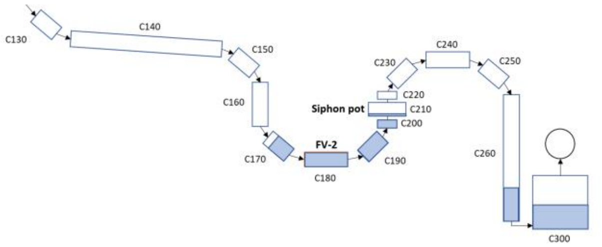


Fig. 5. Residual water level after the drainage (MARS)

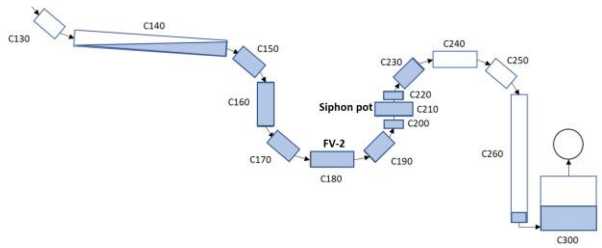


Fig. 6. Residual water level after the drainage (GAMMA+)

After the drainage process was complete, the residual fluid behavior varied between simulations and experimental results. The remaining water levels predicted by MARS-KS and GAMMA+ are shown in Fig. 5 and Fig. 6. The MARS-KS simulation resulted in reasonable water levels observed around the siphon pot and FV-2. MARS-KS results showed that the air-filled space downstream of FV-2 exhibited a pressure approximately 900 Pa lower than the upstream side. As a result, the water level in the FV-2 downstream section was 9 cm higher than the upstream section. In contrast, GAMMA+ predicted that water remained in the DL-2 region, which was totally inconsistent with experimental observations. While repeated experimental trials showed variability in the siphon pot water levels as shown on Fig. 7., the GAMMA+ results did not align with any observed cases, suggesting that GAMMA+ may not capture the siphon break dynamics.

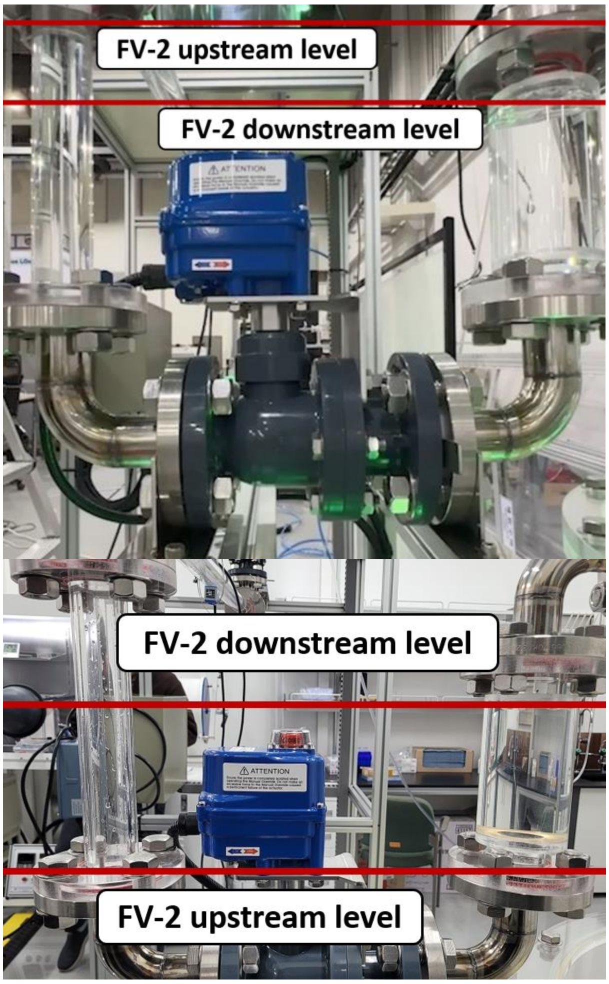


Fig. 7. Residual water level after the drainage during the experiment (Case #1 (up), Case #2 (down))

## 5. Conclusions

This study analyzed the K-MSR fuel salt drain system through scaled experiments and numerical simulations using MARS-KS and GAMMA+. The comparison between the two codes and the experimental results provided insights into the predictive capabilities and limitations of each approach.

The results demonstrated that MARS-KS accurately predicted the overall drain process, including the FSL tank level and siphon pot behavior. In contrast, GAMMA+ better captured the rapid slow-down in drainage near the end of the process, a feature not well represented by MARS-KS. However, MARS-KS provided more accurate predictions for siphon pot water levels and residual fluid distribution, whereas GAMMA+ overestimated water retention in certain regions. These discrepancies highlight the need for further refinement of the GAMMA+ model, particularly in predicting the flow behavior during the siphon break.

Future work will focus on refining the GAMMA+ modeling approach and conducting additional experiments to further validate and enhance the predictive capabilities of both codes.

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