Evaluation of Air-Water Two-Phase Drainage Dynamics in the K-MSR Drain System Using MARS and GAMMA+

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1. Introduction

The fuel salt drain system of molten salt reactors (MSRs) is a fundamental safety feature designed to transfer liquid fuel to subcritical storage tanks during shutdown or emergency conditions. For the system to perform as intended, it is critical to understand not only the overall drainage dynamics but also localized behaviors such as flow regime transitions and residual liquid distribution. Among these, the siphon pot region plays a unique role, as the amount of liquid remaining after drainage may influence freeze valve performance and the overall reliability of the discharge system.

To support design optimization, accurate modeling tools are needed that can predict both the global drainage trend and local details. System analysis codes such as MARS-KS and GAMMA+ are widely used in reactor safety analysis, but their ability to reproduce MSR-specific drainage phenomena—including stratified flow at low liquid levels and residual liquid in the siphon pot—has not been fully demonstrated. Establishing the predictive capability and limitations of these codes is therefore essential for their application to MSR design.

This study addresses that need by comparing scaled water–air experiments with code simulations under different initial water levels (20, 50, and 80 cm). The experimental results reveal key phenomena such as the persistence of horizontal stratified flow at low levels and variations in siphon pot filling, while the code simulations provide insight into where one-dimensional models succeed and where they fall short. Through this comparison, we evaluate the suitability of system codes for predicting drainage behavior in MSRs and discuss their implications for the drain system design.

2. Scaled Experiments

The scaled mock-up of the K-MSR drain system was designed by UNIST and KAERI, fabricated at UNIST, and then delivered to HDEC, where the experiments and subsequent analyses were conducted. The apparatus was constructed at 1/4 scale of the prototype and employed transparent acrylic structures for direct visualization of flow patterns. An orifice was installed at the freeze valve location to reproduce the expected hydraulic resistance, while a motor-operated ball valve was used in place of the prototype freeze valve. These measures allowed the scaled facility to maintain representative pressure-drop characteristics and to ensure that the drainage velocity similarity was adequately satisfied for single-phase flow. A photograph of the apparatus is shown in Fig. 1. and the component dimensions are summarized in Table I.

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

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	

Water was selected as the liquid simulant because its kinematic viscosity is close to that of molten salt, thereby preserving Reynolds number similarity and enabling reproduction of global drainage behavior. Air was used in place of helium. This choice is sufficient for single-phase drainage but does not reproduce strict two-phase similarity. For exact density ratio scaling, water–air experiments would require operation at about 0.041 bar, water–helium at about 0.3 bar, and diiodomethane–helium could achieve the correct density ratio at 1 bar. However, the latter option was dismissed due to the toxicity of diiodomethane and uncertainty of its compatibility with acrylic, while sub-atmospheric operation would have increased the complexity of sealing and pressure equalization, reducing the practicality of repeated experiments. Consequently, the present facility was designed to reproduce overall drainage dynamics while accepting distortion in two phase flow phenomena.

Experiments were first conducted with an initial liquid height of 80 cm, which corresponds to the baseline scaling condition and represents the full inventory of molten salt in the K-MSR core under normal operation. This case forms the primary validation reference for both the mock-up and the system codes. Additional experiments were then performed with 50 cm and 20 cm initial levels, which do not directly correspond to the scaled reference but serve as supplementary scenarios. These cases provide insight into potential situations where drainage may occur with the storage tank partially filled, such as after prior operations or interrupted refilling. In all cases, the drain tank initial level was approximately 12 cm, because the connected drain line is elevated by that amount from the bottom of the tank. This design reflects the fact that in the actual K-MSR, when fuel salt is recharged by pressurizing the drain tank, the liquid below the drain pipe inlet cannot be pushed upward and remains as residual inventory; thus, the 12 cm offset simulates this unavoidable hold-up. The lower-level tests were therefore intended as exploratory studies to assess sensitivity of drainage characteristics under reduced hydrostatic head. Across all conditions, observations included liquid-level evolution, flow regime transitions in the horizontal pipe, and the distribution of residual water in the siphon pot.

3. Simulation Methods

The scaled experiments were complemented by numerical simulations carried out with MARS-KS 2.0 and GAMMA+, which were benchmarked against the experimental data. The computational domains were configured to reproduce the experimental facility as closely as possible in terms of both geometry and boundary conditions.

A key parameter for simulating the drain behavior is the pressure loss across the piping system. Loss coefficients for each element of the apparatus were evaluated and are summarized in Table II. These values were directly implemented in the input decks to capture the hydraulic resistance accurately. To ensure consistency and enable direct comparison, the same set of coefficients was applied in both the MARS and GAMMA+ 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 numerical setup, the experimental loop was subdivided into 20 control volumes with a total of 191 computational nodes, providing sufficient spatial resolution to capture the transient drainage process. The FSL and drain tanks were treated as open volumes under atmospheric boundary conditions. The two freeze valves were modeled as junctions with a specified opening time of 15 seconds, corresponding to the actual valve behavior in the experiments. The resulting nodalization applied to both MARS and GAMMA+ is illustrated in Fig. 2.

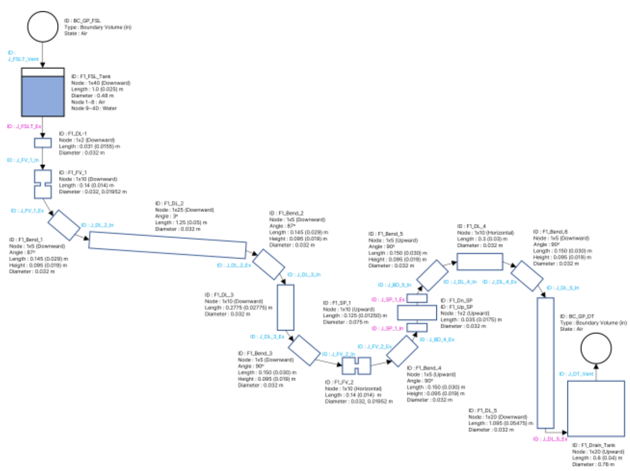

Fig. 2. Nodalization for both MARS and GAMMA+

4. Results and Discussion

The following present the FSL tank water level versus time, comparing experiments with MARS-KS and GAMMA+.

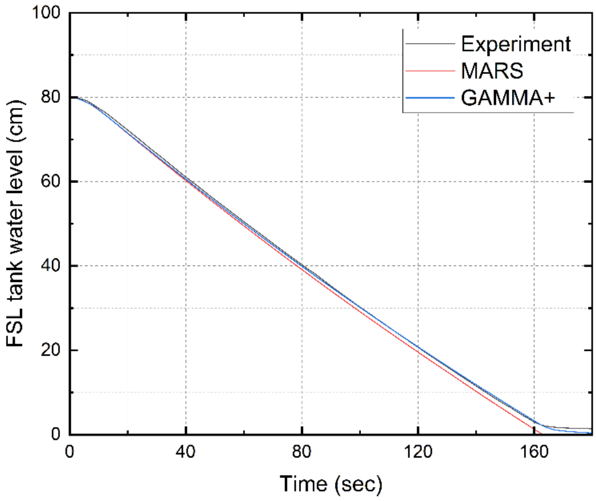

Fig. 3. FSL tank water level through the time (80 cm)

For the 80 cm baseline case (Fig. 3), both codes reproduce the measured level decrease through most of the transient, indicating that the global gravity-driven drainage is well captured under full-inventory conditions. As drainage approaches completion, the experiment shows a distinct reduction in discharge rate. GAMMA+ follows this late-stage slowdown closely and its curve tracks the measured deceleration, whereas MARS does not capture the end-stage flow-rate collapse and continues to drain too quickly relative to the data in the final segment.

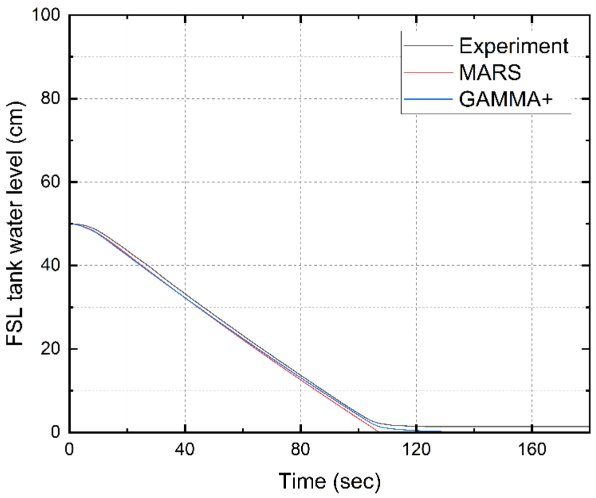

Fig. 4. FSL tank water level through the time (50 cm)

For the 50 cm case (Fig. 4), the experimental drain-rate history is very similar to the 80 cm result, as expected from quasi-steady one-dimensional incompressible behavior. Both codes track the main trend. Near completion the experiment again shows a reduction in flow rate that GAMMA+ reflects, while MARS fails to represent the late-stage drop.

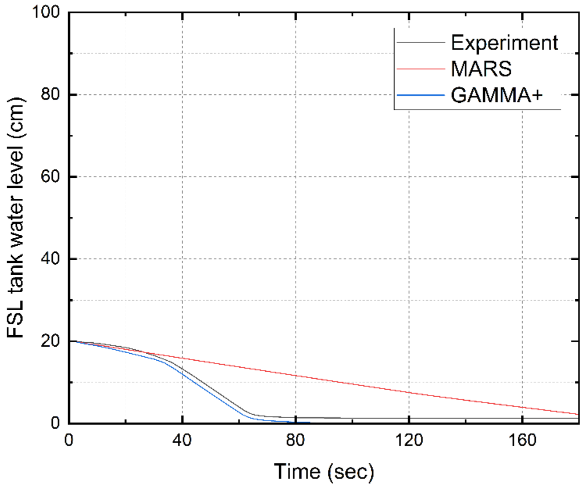

Fig. 5. FSL tank water level through the time (20 cm)

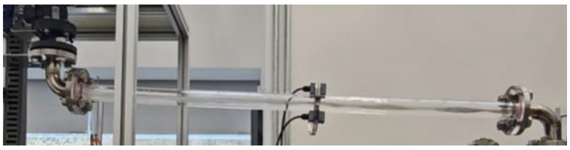

Fig. 6. Horizontal stratified-flow during the drainage

For the 20 cm case (Fig. 5), the experiment exhibits a prolonged horizontal stratified-flow period (Fig. 6) with strong interfacial drag, followed by a transition to single-phase drainage and a clear deceleration near the end due to the build-up of water-air stratified flow. GAMMA+ well reproduces this sequence. It shows a shallow level-decay slope during the extended stratified regime, captures the timing of the transition, and reflects the measured flow slowdown toward completion. MARS does not follow the experimental behavior. It retains a stratified-dominant prediction for whole transient with excessive interfacial drag loss, yields a level decrease that is inconsistent with the measured mid-stage trend, and still does not capture the end-stage deceleration.

Given that both models used the same nodalization, valve opening schedule, and pressure-loss coefficients, these differences are attributed to the two-phase closure and regime-transition treatments. In particular, GAMMA+ shows stronger sensitivity to gas holdup and interfacial shear in horizontal stratified conditions, while MARS’s one-dimensional correlations and transition logic provide limited responsiveness to the buildup and collapse of two-phase effects at low head, leading to the observed mismatch. MARS applies a more rigid flow-regime classification, and under the 20 cm initial level the model does not cross the internal threshold required to transition to single-phase flow, which leads to the observed mismatch.

5. Conclusions

This study compared scaled water and air drainage experiments of the K-MSR mock-up with predictions from MARS-KS and GAMMA+. At initial water level of 80 cm and 50 cm the two codes reproduced the global gravity-driven level decrease seen in the tests. At 20 cm the experiment showed a long stratified period followed by a clear slowdown near completion. GAMMA+ followed this end-stage behavior well. MARS-KS did not capture the late drop in flow rate.

Common expectation was that MARS, with more detailed water-hydraulics models and fewer simplifications, would outperform GAMMA+ for this kinds of water-air drainage experiment. However, in this study, GAMMA+ matched the experiment better. The difference arises from how the codes treat two-phase behavior. GAMMA+ calculates interfacial losses as the gas fraction and therefore reflects the measured deceleration and acceleration of the flow. While, MARS-KS applies a strict flow-regime classification and computes interfacial drag for each regime. Under the 20 cm condition its internal criteria did not trigger a transition to single-phase drainage. The prediction remained stratified-dominant and diverged from the data.

These findings matter beyond MSRs. Gravity-driven discharge through piping with horizontal runs also appears in light-water reactor analyses. Users of MARS-KS should take special care to the flow-regime transition criteria when simulating gravity-driven water–air drainage.

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