

Numerical Analysis of Molten Salt Spreading and Solidification under Leakage Conditions

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1. Introduction

Molten salt reactors (MSRs) are advanced nuclear systems characterized by high-temperature and low-pressure operation, offering improved thermal efficiency and inherent safety features [1]. Despite these advantages, failure of a pipe or drain tank may release high-temperature molten salt into the surrounding environment. The resulting spreading and solidification behavior determines the affected area and thermal loading and is therefore important for the design of spill-management and containment systems.

Previous studies have examined molten-salt spreading and solidification using numerical approaches [2–5]. These studies showed that the initial spreading is primarily driven by gravity and flow momentum, whereas subsequent propagation is increasingly restricted by solidification near the advancing front. However, most previous MSR leakage studies considered relatively small leak flow rates, typically on the order of 0.01 kg/s or lower. Consequently, the behavior of molten salt under rapid, large-scale release conditions associated with major pipe rupture or drain-tank failure remains insufficiently understood.

This study numerically investigates the spreading and solidification of FLiNaK under leak flow rates of 1–20 kg/s, total leakage amounts of 20–40 L, and various surrounding-structure temperatures. The volume-of-fluid method, enthalpy-porosity model, and discrete-ordinates radiation model were employed to simulate molten-salt flow, solidification, and radiative heat transfer, respectively. The results demonstrate that the spreading behavior is governed by competition between the momentum supplied by the incoming salt and the resistance caused by solidification. Momentum-dominant conditions produced extensive spreading, hydraulic jumps, and post-leak film motion, whereas solidification-dominant conditions resulted in front blockage and stepwise propagation. These findings provide a basis for evaluating large-scale molten-salt leakage during MSR accident scenarios.

2. Methods and Results

2.1 Numerical Model

The leakage of FLiNaK onto a horizontal steel plate was simulated using the two-dimensional axisymmetric

domain shown in Fig. 1. Molten salt at 650°C was discharged through a 0.14-m-long vertical pipe positioned 0.01 m above a 6.35-mm-thick plate. Leak flow rates of 1, 5, 10, 15, and 20 kg/s and total leakage amounts of 20, 30, and 40 L were examined at surrounding-structure temperatures of 50, 225, and 400°C. The radial extent of the domain was 3 m, and a heat transfer coefficient of 10 W/m²K was applied beneath the plate.

The molten-salt-air interface was captured using the volume-of-fluid method, while solidification was described using the enthalpy-porosity model. Radiative heat transfer from the high-temperature salt was included using the discrete-ordinates model. The simulations were performed with Ansys Fluent 2021 R1 using PISO pressure-velocity coupling, QUICK discretization, and a modified HRIC interface scheme. A grid-independence test led to the use of approximately 124,600 cells.

To confirm the reliability of this modeling approach, two independent validation cases were additionally considered. The FLiNaK leakage scenario examined by An and Kim [3], corresponding to the ANL/CFCT-22/15 conditions with an ambient temperature of 26.85°C, an adiabatic bottom boundary, a leak rate of 0.0067 kg/s, and a total discharge of 5 L, was reproduced using the present model. As shown in Fig. 2(a), the predicted spreading-front position matched the reference result [3] within a maximum difference of 0.2% throughout the discharge period.

Because no experimental data are currently available for the spreading and solidification of leaked FLiNaK, the methodology was further verified against a spreading experiment with a low-melting-point metal alloy (U-alloy) reported by Yokoyama et al. [6]. As compared in Fig. 2(b), the predicted growth of the spreading area during the coupled spreading-solidification process remained within a maximum deviation of 2.7% from the measured values. These two comparisons indicate that the present numerical settings, which were kept unchanged for all cases discussed below, are suitable for capturing the coupled spreading and solidification behavior of leaked molten salt.

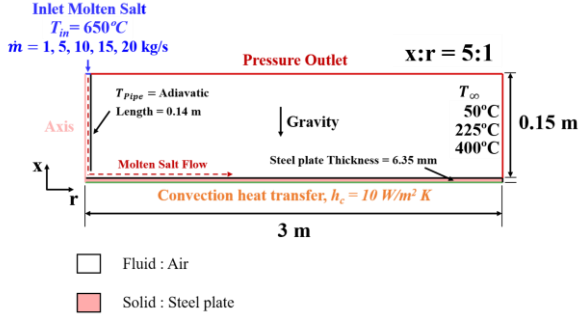


Fig. 1. Computational domain and boundary conditions for molten-salt leakage, spreading, and solidification.

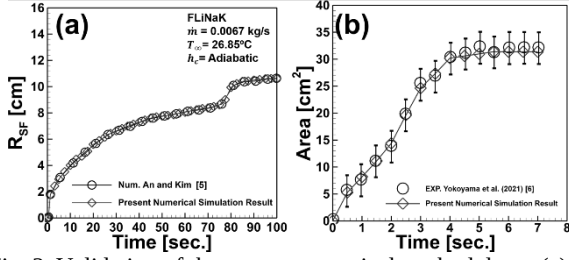


Fig. 2. Validation of the present numerical methodology: (a) spreading-front position compared with An and Kim [3]; (b) spreading area compared with the experiment of Yokoyama et al. [6].

2.2 Effect of Leak Flow Rate

All 45 cases were continued until the molten-salt film stopped moving after leak termination. At 50°C and a fixed leakage amount of 20 L, the final spreading distances were 92.9, 119.5, 144.8, and 165.2 cm at 1, 5, 10, and 20 kg/s, respectively. Thus, the spreading distance differed by a factor of approximately 1.7 even though the discharged amount was identical. A larger leak flow rate supplied greater forward momentum and sustained the motion after the leak ended. The additional advancement after termination increased from 1.9 cm at 1 kg/s to 27.7 cm at 15 kg/s. Hydraulic jumps and film separation were also observed, while back-drift of the separated film became weaker as the leak flow rate increased.

2.3 Momentum-Solidification Competition

At low leak flow rates, solidification began before the leak ended and a locally thick solid layer developed near the spreading front. This layer acted as a dam, causing upstream accumulation, partial remelting, and stepwise front advancement. Consequently, the final spreading distance did not always increase with surrounding temperature; at 5 kg/s, the distance at 225°C was shorter than that at 50°C. At high flow rates, the film advanced rapidly before extensive solidification occurred, and the spreading distance increased consistently with temperature. Figure 3 summarizes these solidification- and momentum-dominant regimes. Across all conditions, 20 L released at 20 kg/s and 400°C spread more than twice as far as 40 L released at 1 kg/s and 50°C, demonstrating that leakage amount alone cannot determine the affected area.

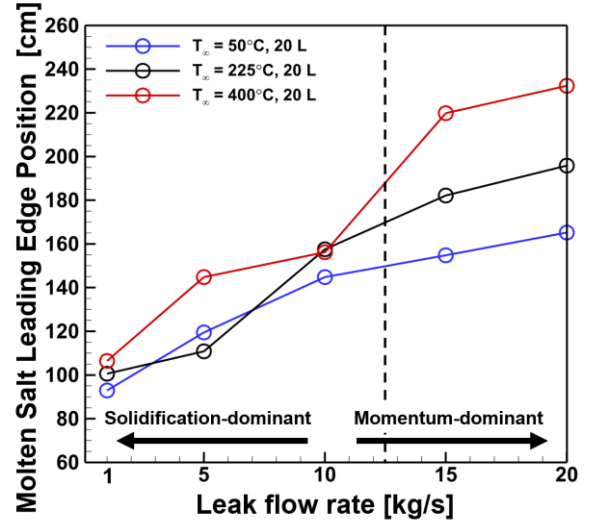


Fig. 3. Final spreading distance at $V = 20$ L, illustrating the transition between solidification- and momentum-dominant behavior.

3. Conclusions

This study numerically investigated the spreading and solidification of FLiNaK under large-scale leakage conditions. The results showed that the final spreading distance was governed by competition between the incoming momentum and progressive solidification rather than by the total leakage amount alone. At low leak flow rates, solidification near the spreading front obstructed film propagation and caused stepwise advancement and non-monotonic temperature dependence. At high flow rates, stronger momentum promoted wider spreading and greater post-leak advancement. For the same leakage amount of 20 L, the final spreading distance differed by a factor of approximately 1.7 depending on the leak flow rate. These findings indicate that leak flow rate, surrounding temperature, and total leakage amount should be considered together when establishing spill-management criteria for MSR systems.

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