Three-dimensional numerical simulation for the molten salt spreading behaviour

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1. Introduction

The Molten Salt Reactor (MSR) is considered a safer alternative to conventional light-water reactors (LWRs), as it eliminates the risk of core meltdown and has lower radioactive material release during accidents. Even if a leak occurs, the small amount of fission products and low decay heat allow the molten salt to solidify quickly, preventing further accident progression. Based on these safety features, research is underway to miniaturize and modularize MSRs for applications such as ship propulsion and transportation power sources [1].

To commercialize MSRs, their safety must be experimentally verified. Although molten salt is expected to solidify upon leakage, it is essential to quantify the solidification time and behavior. These factors directly impact the release of fission products and must be considered in accident management strategies.

A 2022 study by Argonne National Laboratory (ANL) applied the MELTSPREAD code [2], initially developed for LWRs, to MSRs. The analysis modeled a scenario where 5 liters of molten salt leaked at 12 liters per hour through a 1/4 inch breach. Results showed that when decay heat was considered, heat transfer to the surroundings was insufficient, causing the temperature to rise, highlighting the need for cooling systems during leakage.

Another ANL experiment in 2022 examined NaCl-UCl_3 molten salt leakage, revealing that the molten salt did not solidify even after reaching the catch pan's edge [3]. The spread rate increased with higher initial temperatures and flow rates.

Salt spills are considered the most severe MSR accident, similar to LWR severe accidents. Understanding molten salt behavior is critical for evaluating coolability, fission product release, and reactor integrity. This study simulates molten salt spreading to determine the solidification distance. Since three-dimensional analyses are computationally demanding, three-dimensional simulations are conducted with ANSYS Fluent (2024 R1) [4].

2. Numerical Simulation Method

2.1 Numerical modeling

In the event of a pipe break or vessel failure in a molten salt reactor, the discharge rate and angle of the molten salt release vary depending on the accident scenario. A vessel rupture, in particular, can result in a large release of molten salt, with the impact angle depending on the rupture's location and size. To analyze real reactor conditions, scenarios involving molten salt interaction with floors and sloped surfaces must be considered.

However, in this study, a simplified case, similar to ANL's study, is analyzed. This involves a low flow rate of molten salt discharged vertically onto a flat surface. Spill conditions and molten salt properties are provided in Table I and Table II.

Table I. Simulation conditions

Initial salt temperature	650 °C
Total discharged volume, mass	5 L, 10.1 kg
Volumetric flow rate	12 L/hr
Discharge duration	25 min
Substrate material, thickness	Stainless steel, 6.35 mm
Radius of impinging jet	5 mm
Initial decay heat level	12.38 kW/kg

Table II. Thermophysical properties of FLiNaK

Liquid, solid density	2020, 2200 kg/m^3
Dynamic viscosity	0.00318 kg/m·s
Liquid and solid specific heat	1952 J/kg·K
Liquid and solid conductivity	0.85 W/m·K
Latent heat of fusion	3.99 × 105 J/kg
Surface tension	0.179 N/m

In the MELTSPREAD analysis, molten salt is released through a nozzle with a 5mm radius at a flow rate of 0.0067 kg/s from a height of 10mm above a flat plate. To allow sufficient spreading, the computational domain was designed with a 500mm radius and a height of 160mm in the radial direction, as illustrated in Figure 1. Pressure outlet conditions were set for the upper and side boundaries, while convective heat transfer conditions were applied to the bottom surface of the plate.

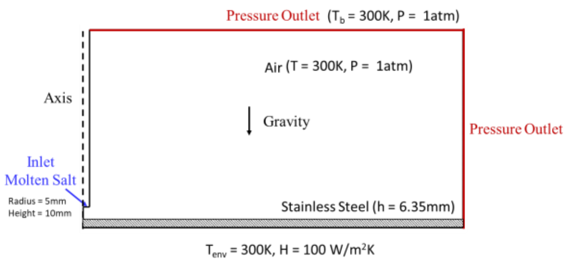
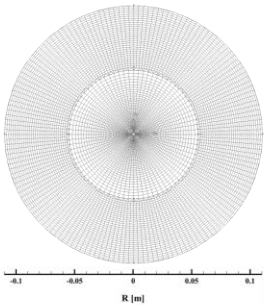
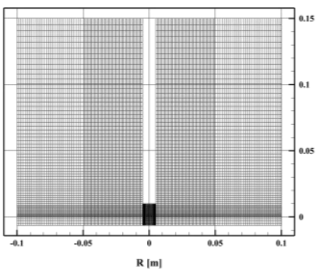


Fig.1 Configuration and boundary conditions



(a) Top view



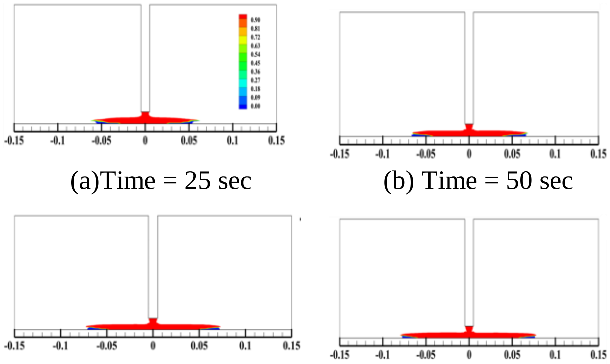
(b) Side view

Fig.2 Three dimensional node system

2.2 Numerical methods

This study employed the commercial computational fluid dynamics software FLUENT [4]. The two-phase flow generated during molten salt cooling was simulated using the Volume of Fluid (VOF) method [5]. Turbulence was modeled with the realizable k-ε model and standard wall functions, while radiation heat transfer was simulated using the discrete ordinate (DO) model. A transient analysis was performed for 200 seconds with a time step of 0.01 seconds. Decay heat was incorporated through a user-defined function (UDF) based on its temporal variation.

To visualize molten salt spreading in a three-dimensional axisymmetric domain centered on the discharge nozzle, the time-dependent liquid fraction was analyzed along the cross-section through the nozzle's central axis, as shown in Figure 3. Due to axisymmetry, the spreading and solidification occur symmetrically on both sides of the center axis. Solidification begins near the upper and lower regions of the leading edge and expands radially over time. Additionally, heat loss due to convective transfer with the bottom surface is more significant than with the upper air, leading to more active solidification in the lower region.

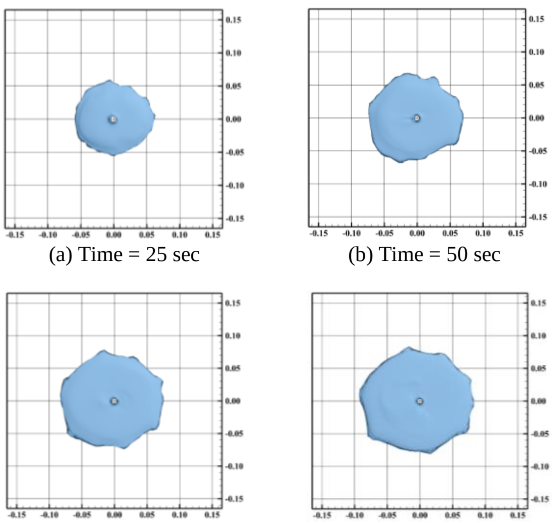


(a)Time = 25 sec (b) Time = 50 sec

(c) Time = 75 sec (d) Time = 100 sec

Fig.3 The evolution of liquid fraction by molten salt spreading in three-dimensional analysis

Figure 4 presents a top-down view of the molten salt spreading process, depicted using VOF values. Regions with a VOF value of 0.5 or higher indicate the liquid phase, while the remaining areas correspond to the gas phase. As the molten salt exits the nozzle, it spreads relatively evenly in the circumferential direction. However, unlike cases without solidification (not shown here), the solidification occurring at the upper and lower regions of the leading edge disrupts uniform radial spreading. This happens because solidification at the leading edge forms an irregular local crust on the molten salt's surface, leading to uneven distribution of solidified regions along the circumference.

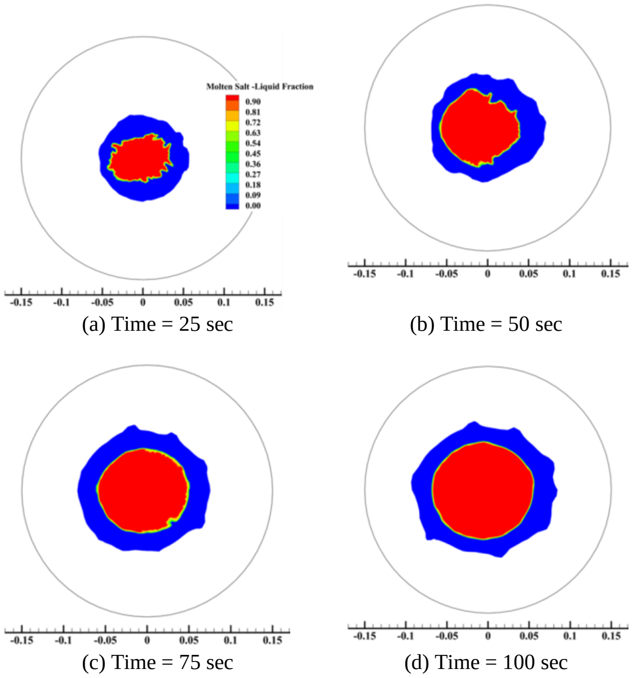


(a) Time = 25 sec (b) Time = 50 sec

(c) Time = 75 sec (d) Time = 100 sec

Fig.4 The evolution of molten salt spreading

Figure 5 depicts the evolution of the solidified region on the bottom surface as the molten salt spreads. The lower surface exhibits a larger solidified area compared to the upper surface. Over time, this solidified region expands radially outward. However, as seen in Figure 4, the solidification at the bottom is not uniformly distributed along the circumference. This non-uniformity arises from the formation of an irregular crust as the molten salt solidifies, leading to varying flow resistance in the circumferential direction.



(a) Time = 25 sec (b) Time = 50 sec

(c) Time = 75 sec (d) Time = 100 sec

Fig.5 The evolution of liquid fraction on the bottom surface of molten salt

As illustrated in Figures 4 and 5, the non-uniform circumferential characteristics are shown in three dimensions. In severe accident scenarios, the spread area directly influences the release of fission products, making the spreading distance a key parameter in numerical analysis. Similar to the irregular circumferential spreading observed in Figure 5, the changes in the leading edge over time do not follow a uniform pattern.

3. Discussions

When molten salt leaks onto a relatively cold surface, solidification occurs at the top and bottom near the leading edge as it spreads. In three-dimensional analysis, crust formation on the surface creates irregular flow resistance, leading to non-uniform circumferential spreading despite the axisymmetric nature of the problem. Future work will extend the comparison across a broader time range and different boundary conditions to further assess the accuracy of two-dimensional CFD analysis in axisymmetric cases. Additionally, experimental validation of 3D FLUENT simulations is planned.

ACKNOWLEDGEMENTS

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