

## Numerical Validation of Molten Salt Spill and Solidification Behaviors using ANSYS Fluent and OpenFOAM

Ye Hwan Chun <sup>a</sup>, Juhyeong Lee <sup>a</sup>, JinHo Song <sup>a</sup>, and Sung Joong Kim <sup>\*a,b</sup>

<sup>a</sup> Department of Nuclear Engineering, Hanyang University

222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

<sup>b</sup> Institute of Nano Science and Technology, Hanyang University

222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

\* Corresponding author: [sungjkim@hanyang.ac.kr](mailto:sungjkim@hanyang.ac.kr)

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### 1. Introduction

Molten Salt Reactors (MSRs) are attracting significant global attention as a next-generation nuclear technology, distinguished by exceptional thermal efficiency and inherent safety features that facilitate carbon neutrality and advanced industrial applications. By employing liquid fluoride or chloride salts as both fuel and primary coolant, MSRs eliminate the core meltdown accidents common to PWRs. Moreover, the temperature-dependent density variations of the high-temperature liquid fuel provide strong negative reactivity coefficients, ensuring robust passive safety. Nevertheless, the successful commercialization and regulatory approval of MSRs require rigorous safety assessments supported by highly reliable numerical analyses or experimental data [1-3].

Among various postulated accident scenarios, a molten salt spill is a critical event in which the primary circuit boundary fails, leading to the leakage of high-temperature salt onto surrounding structures. Given the high melting point of the fuel salt, the spilled material is expected to undergo rapid solidification, fundamentally restricting the mobility and dispersion of radioactive fission products shown in Fig. 1. Therefore, accurately characterizing the spreading dynamics, cooling kinetics, and solidification behavior of the spilled salt is essential for evaluating radiological consequences [4].

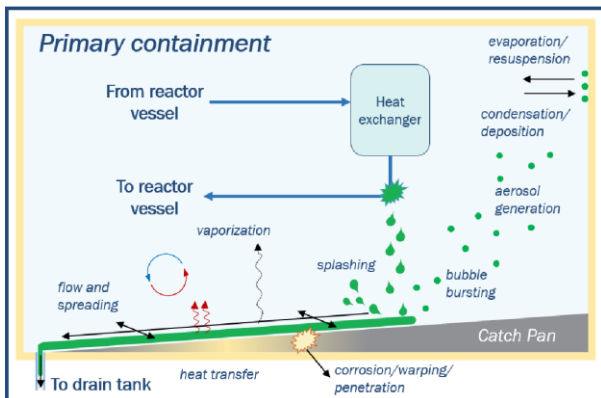


Figure 1. Schematic that depicts molten salt spilling from a leak in the primary loop of a MSR onto a catch pan [4]

Whereas previous research on salt spill dynamics has primarily relied on one-dimensional system codes, there is an increasing demand for advanced three-dimensional computational fluid dynamics (CFD) methodologies to more accurately capture the intricate multiphysics phenomena involved [5]. Simulating these events presents substantial challenges, as it requires resolving multiphase flow interactions alongside strongly coupled heat transfer mechanisms, including thermal radiation and phase change during solidification. The reliability of these numerical assessments is critically dependent on the selection and parameterization of physical models, particularly solidification formulations and interface tracking algorithms. Previous study observed that the molten salt exhibited flow behavior even after solidification. Therefore, verifying the mushy zone modeling using OpenFOAM was necessary [6].

In this study, a comparative numerical assessment of molten salt spreading and solidification is conducted using two prominent CFD codes, ANSYS Fluent and OpenFOAM. Specifically, the research evaluates the implementation of mushy zone modeling, a transitional region that governs flow resistance during phase change, and cross-verifies the resulting spreading radius of the spilled salt.

### 2. Numerical Methods

#### 2.1 Solidification Model

The phase change of the molten salt is governed by the enthalpy-porosity formulation in both CFD codes. The liquid fraction ( $\beta$ ) is computed based on the local temperature, ranging from 0 in the fully solidified state to 1 in the fully liquid region. As the molten salt cools and solidifies, the porosity of the medium decreases. This flow resistance is modeled by adding a momentum sink term ( $S$ ) to the Navier-Stokes equations, which damps the fluid velocity in Eq (1).

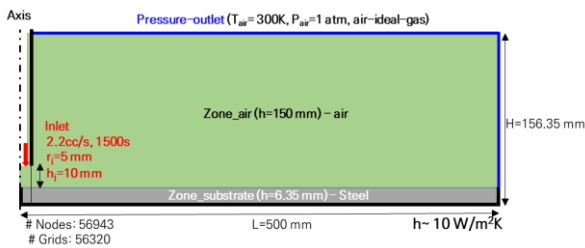
$$S = -\frac{(1-\beta)^2}{(\beta^3 + \epsilon)} A_{mush} \vec{v} \quad (1)$$

where epsilon ( $\epsilon$ , 0.001) is a small computational constant to prevent division by zero,  $v$  is the velocity vector, and  $A_{\text{mushy}}$  is the mushy zone constant that varied among  $1E4$ ,  $5E4$ , and  $1E5$  to evaluate the sensitivity of the solidification model and its impact on the spreading radius in each solver.

## 2.2 Numerical settings

To capture the free-surface flow and thermal interactions during the molten-salt spill, both ANSYS Fluent and OpenFOAM are used, with the RANS(SST  $k$ - $\omega$ ) solver coupled to the Volume of Fluid (VOF) method. In OpenFOAM, the transient multiphase dynamics are resolved using the icoReactingMultiphaseInterFoam solver, which accommodates multiple phases, including liquid, gas, solid, and the solid substrate. In ANSYS Fluent, phase transitions and associated multiphase flow dynamics are simulated by coupling the VOF model with the Solidification and Melting model.

Figure 2 shows a two-dimensional axisymmetric computational domain is constructed for the molten salt spill simulation. The geometry includes a steel substrate with a 500 mm radius and a thickness of 6.35 mm. The fluid domain height is 150 mm. To represent a continuous liquid supply, an inlet with a 5 mm radius is located at a height of 10 mm. This setup mitigates an impinging jet. The domain is discretized using a structured quadrilateral mesh approximately 56,320 cells are generated. The near-wall grid spacing maintains  $y^+$  values below 5. This identical mesh is used in both ANSYS Fluent and OpenFOAM.



**Figure 2.** Geometry of molten salt spreading CFD simulation

Table 1 summarizes the boundary conditions for the molten salt spill simulation. A continuous mass flow rate of 0.0067 kg/s is applied for 1,500 seconds. The initial temperature of the molten salt is 923 K. Table 2 lists the thermodynamic properties of the molten salt mixture. Temperature dependent properties such as density, dynamic viscosity, specific heat, thermal conductivity, and surface tension are applied. A latent heat of 144 kJ/kg is specified for the phase change calculations.

**Table 1.** Boundary conditions of molten salt spreading numerical simulations

Spill condition	Values
Salt composition	NaCl-KCl- $UCl_3$
Initial salt temperature	923K
Total spill mass	10.05kg
Mass flow rate	0.0067kg/s
Spill duration	1,500s
Substrate material	Steel
Substrate thickness	6.35mm
Radius of spill jet	5mm

**Table 2.** Thermodynamic properties of molten salt

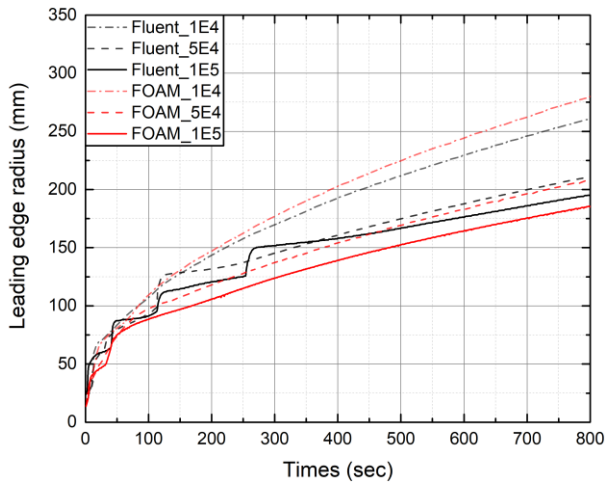
Properties	Values
Composition	NaCl-KCl- $UCl_3$
Melting point [K]	743.3
Density [ $kg/m^3$ ]	3476 ~ 2875
Dynamic viscosity [ $kg/m \cdot s$ ]	10 ~ 0.001257
Specific heat [ $J/kg \cdot K$ ]	609.5 ~ 547.5
Thermal conductivity [ $W/m \cdot K$ ]	0.407 ~ 0.319
Latent heat [kJ/kg]	144
Surface tension [mN/m]	126.9 ~ 110.3
Radiation emissivity	1.0

## 3. Results

A mesh sensitivity analysis is conducted using eight models with cell counts ranging from 11,320 to 112,884. A denser mesh reduces the spreading radius. The 11,320-cell mesh results in a spread radius of 268 mm. The 112,884-cell mesh shows 253 mm. The 56,320-cell mesh is selected for the numerical simulations to balance computational time and accuracy.

Figure 3 shows the leading edge radius over 800 seconds for ANSYS Fluent and OpenFOAM. The mushy zone constant is varied among  $1E4$ ,  $5E4$ , and  $1E5$ . A lower mushy zone constant of  $1E4$  produces a larger spreading radius in both codes. A higher constant of  $1E5$  increases flow resistance in the solidification region and reduces the spreading radius.

At 800 seconds, the  $1E4$  case reaches approximately 280 mm in OpenFOAM and 260 mm in Fluent. The  $1E5$  case reaches approximately 185 mm in OpenFOAM and 195 mm in Fluent. The  $5E4$  cases show similar results between the two codes at approximately 210 mm. The Fluent results display step like increases in the spreading radius over time. The OpenFOAM results exhibit a smoother continuous increase. Both codes demonstrate similar increasing trends in the spreading radius for each mushy zone constant.



**Figure 3.** Leading edge radius of molten salt for different mushy zone constants in ANSYS Fluent and OpenFOAM

#### 4. Conclusion

This study evaluated molten salt spreading and solidification using ANSYS Fluent and OpenFOAM. The mushy zone constant varied among 1E4, 5E4, and 1E5. A higher constant increased flow resistance in the solidification region and reduced the spreading radius. Both solvers demonstrated similar overall spreading trends for each constant. These results provide numerical guidelines for the safety assessment of molten salt reactor spill accidents.

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