Effect of Spill Out Time on Spreading Distance in Molten Salt Reactor using ANSYS-Fluent

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1. Introduction

As a part of small reactor developments for the GEN-IV (Generation IV) reactors, a MSR (Molten Salt Reactor) is selected for reactor technology and safety aspects worldwide. In the MSRs, the molten liquid salt is the fuel and the cooling liquid at the same time. The first MSR was developed in the USA from 1,960 till 1,970 years, which was thermal-neutron-spectrum graphite moderated concepts [1]. Since 2005, European R&D (Research and Development) interest has focused on fast neutron MSR (MSFR) as a long-term alternative to solid-fueled fast neutrons reactors [2]. The general characteristics of MSR is molten fluorides or chloride salt as fuel fluid and low-pressure, high boiling-point coolant. In a safety of the MSR, the most important thing is a loss of the molten fuel salt with the coolant in the primary system. The spreading and heat transfer behavior of radionuclide-bearing molten salt directly and indirectly affect the distribution of radionuclides during and after a salt spill accident. For this reason, the spreading and cooling process of the spill molten salt is very important for MSR safety.

Test and analysis on the spreading and cooling of the spill molten salt was performed in the SNL (Sandia National Laboratory) recently [3, 4]. Tests were conducted using a chloride salt composition representative of fast spectrum MSRs (eutectic NaCl-UCl_3) to highlight individual processes expected to affect the fate of spill molten fuel salt and the radionuclides within during a salt spill accident. Spreading and cooling of the spill molten salt were analyzed using the MELTSPREAD computer code [5] for a scenario of molten FLiNaK spilling onto a flat stainless-steel substrate. MELTSPREAD was developed at ANL to model the one-dimensional flowing and freezing of molten corium for PWR (Pressurized Water Reactor) and was applied to model molten salts. The MELTSPREAD model on the molten salt was updated using a corrected heat of fusion value of FLiNaK and to accommodate a larger salt spill volume. The model was run with and without the inclusion of contributions from decay heat and a sensitivity analysis of initial spill conditions was performed to determine the importance of those factors on model outcome. The results provide insight into the expected spreading and heat transfer behavior of simulated and irradiated fuel salt that has been spilled.

Preliminary analysis on spreading and cooling in PWR was widely studied for severe accident mitigation [6]. The developed methodology for corium spreading may be used for spreading of the molten salt for the MSR. Preliminary comparison analysis on spreading distance and time of the spill molten salt in MSR with corium in PWR was performed using a simple analytical model [7] and preliminary analysis on spreading distance and time of the spill molten salt using ANSYS-Fluent [8, 9, 10].

Analysis on spreading distance of the spill molten salt as salt composition of KCl-UCl_3 for very small MSR or KCl-NaCl-UCl_3 for marine MSR has been performed using the ANSYS-Fluent computer code of CFD (Computational Fluid Dynamics) tool. This is focused on effect of spill out time of 20 sec, 40 sec, 80 sec, 100sec on spreading distance in spill molten salt accident .

2. Input Model for ANSYS-Fluent Analysis

Input model for ANSYS-Fluent analysis on spreading and cooling of the spill molten salt was developed. Fig. 1 shows ANSYS-Fluent input model for spreading analysis of the spill molten salt. Fig. 2 shows ANSYS-Fluent mesh for spreading of the spill molten salt.

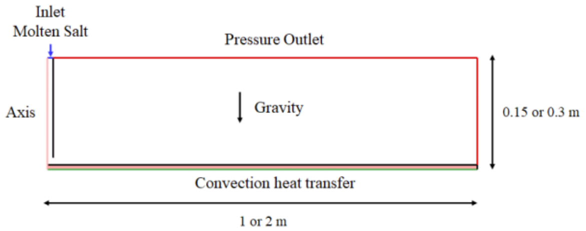

Fig. 1 ANSYS-Fluent input model for spreading analysis of the spill molten salt.

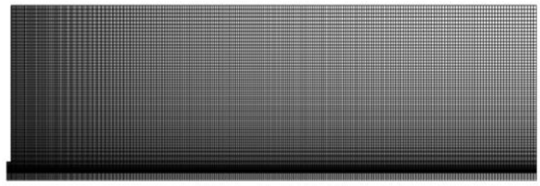

Fig. 2 ANSYS-Fluent mesh for spreading and cooling analysis of the spill molten salt.

In this study, the following conditions are used.

- Spill molten salt: KCl-UCl_3(47-53 mol%) or KCl-NaCl-UCl_3(20.3-42.9-36.8 mol%) or
- Mass flow rate of spill molten salt: 0.1 kg/s to 20 kg/s for 20 sec, 1 kg/s or 2 kg/s for 100 sec, 5 kg/s for 40 sec or 80 sec
- Initial salt temperature: 923 K
- Solidification temperature: 743 K of 809 K of KCl-UCl_3 or KCl-NaCl-UCl_3
- Temperature of flat floor, atmosphere, and surrounding structures: 630 K
- Geometry: length 100 cm or 200 cm, height 15 cm or 30 cm
- Bottom plate thickness: 6.35 mm
- Number of mesh: 32,000
- Time step: 0.01 sec, Calculation time: 120 sec
- Analysis method: two-dimensional Axisymmetric
- Bottom condition: hear transfer coefficient input of 10 $W/m^2.K$

And the following models are used.

- Multiphase model: VOF (Volume Of Fluid)
- Viscous model: K-epsilon, Realizable
- Mushy zone parameter on solidification & melting model: 1e+5
- Radiation model: Discrete Ordinates
- Pressure-velocity coupling: PISO
- Volume fraction scheme: Compressive
- Spatial discretization: Second Order Upwind

Table I shows material properties of spill molten salt of KCl-UCl_3 and KCl-NaCl-UCl_3 in ANSYS-Fluent analysis. In general, solidification temperatures and latent heat of fusion are very effective on the spreading distance of the spill molten salt. The Solidification temperature of KCl-UCl_3 is higher than that of KCl-NaCl-UCl_3, but the latent heat of fusion of KCl-UCl_3 is less that of KCl-NaCl-UCl_3.

Table I: Material properties of spill molten salt in ANSYS-Fluent analysis.

	KCl-UCl_3	KCl-NaCl-UCl_3
Composition (%)	47-53	20.3-42.9-36.8
Solidification Temperature (K)	809	743
Density (kg/m^3)	3,654	3,282
Specific Heat (J/kg.K)	475	570
Thermal Conductivity (W/m.K)	0.283	0.38
Dynamic Viscosity (m^2/s)	7.86 x 10^{-7}	7.23 x 10^{-7}
Latent Heat of Fusion (J/kg)	68,000	144,657

3. Results and Discussion

Figs. 3 and 4 show ANSYS-Fluent results on spreading distance and temperature distribution of the spill molten salt of KCl-UCl_3 in case of 20 kg/s for 20 sec, respectively. The red color means liquid salt. Solidification of the molten salt changes color, as shown in Fig. 3.

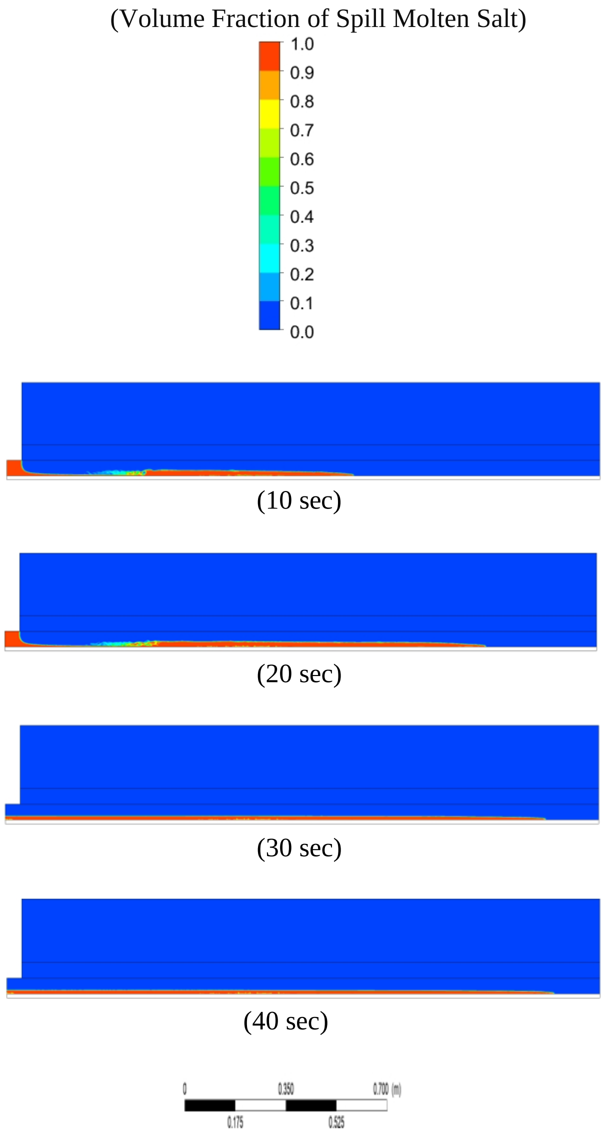

Fig. 3 ANSYS-Fluent results on spreading distance of the spill molten salt with time increase (KCl-UCl_3).

The spreading distance affects the temperature distribution. The spreading distance of spill molten salt of KCl-UCl_3 estimates as approximately 1.62 m cm at 20 sec in condition with the mass flow rate of the spill molten salt of 10 kg/s for 20 sec and initial salt temperature of 923 K. After this time, the spreading distance increases gradually to 120 sec, because the spill out of the molten salt was stopped at 20 sec. Finally, the spreading distance of spill molten salt is 1.85 m at 120 sec.

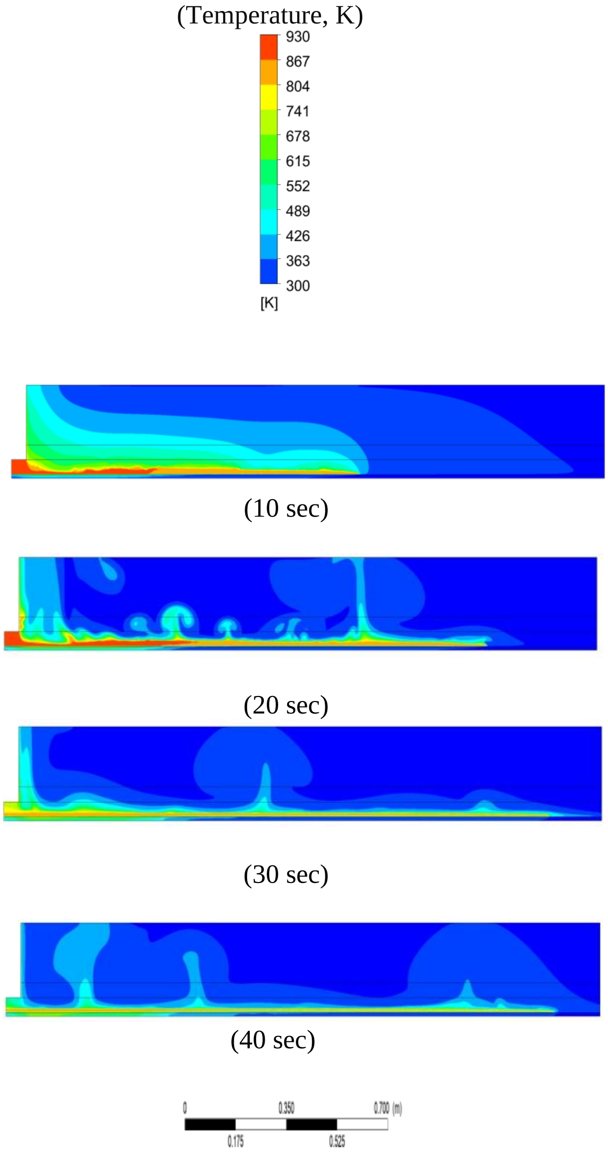

Fig. 4 ANSYS-Fluent results on temperature distribution of the spill molten salt with time increase (KCl-UCl_3).

Fig. 5 shows ANSYS-Fluent results on spreading distance of the spill molten salt with increase in spill mass flow rate as salt composition of KCl-UCl_3 . In general, increase in the spill mass flow rate leads to increase in spreading distance. The spreading distance of the spill molten salt rapidly increases for initial 20 sec. After this time, the spreading distance increases gradually to 120 sec, because the spill out of the molten salt was stopped at 20 sec. The spreading distance increases significantly and proportionally as the leaking molten salt flow rate increases from 0.1 kg/s to approximately 1 kg/s. However, the spreading distance does not increase proportionally with subsequent increases in the leaking molten salt flow rate. As shown in the figure, the spreading distance increases significantly when the leaking molten salt flow rate increases from 0.1 kg/s to 10 kg/s.

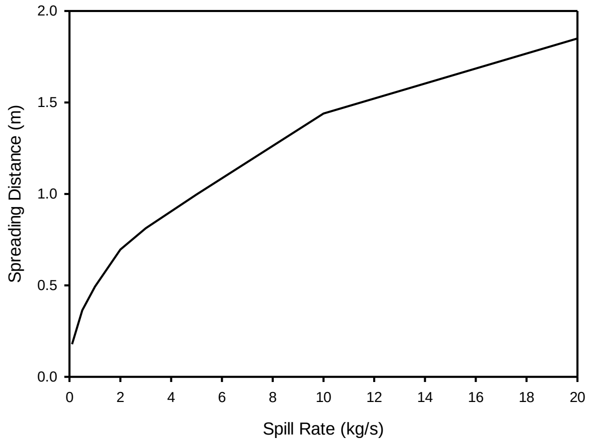

Fig. 5 ANSYS-Fluent results on spreading distance of the spill molten salt for 20 sec as function of spill mass flow rate (KCl-UCl_3).

Figs. 6, 7, and 8 show the ANSYS Fluent analysis results for the spread distance of a KCl-UCl_3 molten salt leak of 100 kg (for 20 sec, 100sec), 200 kg (for 20 sec, 40 sec, and 100 sec) 400 kg (for 20 sec or 80 sec), respectively. As shown in the figures, the spreading distance is longer when a larger amount of the same mass leaks initially. Since the leaked molten salt solidifies due to heat transfer with the surroundings while spill out time, the spreading distance does not change linearly over time.

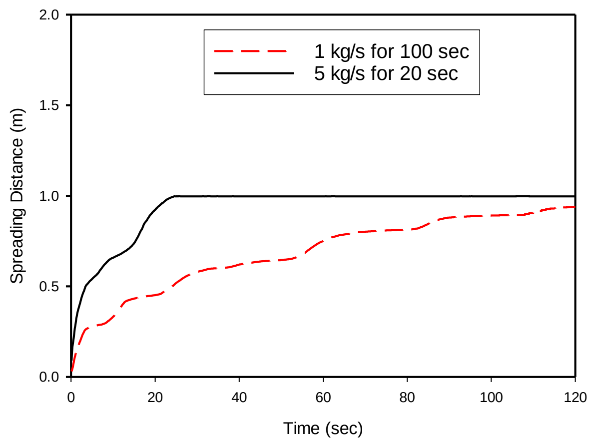

Fig. 6 ANSYS-Fluent results on spreading distance of the spill molten salt of 100 kg for 20 sec or 100 sec (KCl-UCl_3).

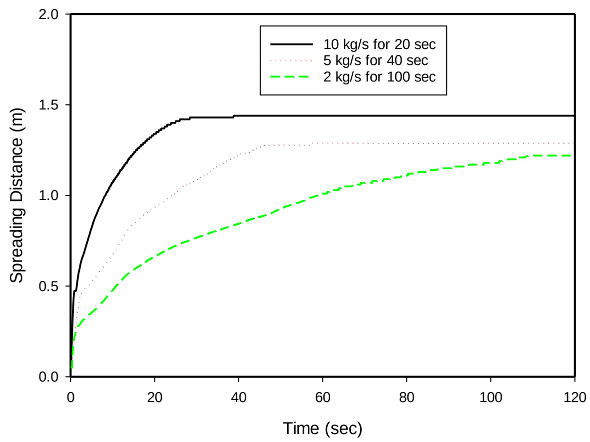

Fig. 7 ANSYS-Fluent results on spreading distance of the spill molten salt of 200 kg for 20 sec, 40 sec, 100 sec (KCl-UCl_3).

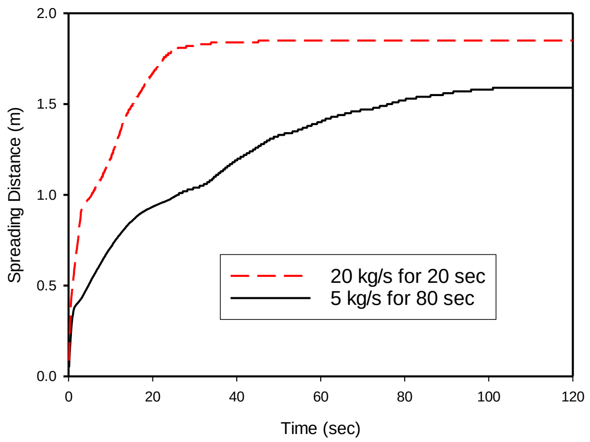

Fig. 8 ANSYS-Fluent results on spreading distance of the spill molten salt of 400 kg for 20 sec or 80 sec (KCl-UCl_3).
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4. Conclusions

Analysis on spreading distance for the spill molten salt has been performed using the ANSYS-Fluent computer code. The spreading distance of spill molten salt of KCl-UCl_3 estimates as approximately 1.62 m cm at 20 sec in condition with the mass flow rate of the spill molten salt of 20 kg/s for 20 sec and initial salt temperature of 923 K. After this time, the spreading distance increases gradually to 120 sec, because the spill out of the molten salt was stopped at 20 sec. Finally, the spreading distance of spill molten salt is 1.85 m at 120 sec. The spreading distance increases significantly and proportionally as the leaking molten salt flow rate increases from 0.1 kg/s to approximately 1 kg/s. However, the spread length does not increase proportionally with subsequent increases in the leaking molten salt flow rate. The spreading distance is longer when a larger amount of the same mass leaks initially. Since the leaked molten salt solidifies due to heat transfer with the surroundings while spill out time, the spreading distance does not change linearly over time. More calculations for the spill molten salt are necessary to estimate effect of the main parameters, such as material properties and spreading channel condition. As the next step, more detailed analysis on spreading and cooling of the spill molten salt including complex heat transfer is necessary to verify the present results.

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