Preliminary Analysis on Spreading Distance of Spill Molten Salt as Salt Composition 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. Fig. 1 shows spreading and cooling concept of the spill molten salt in an environment condition.

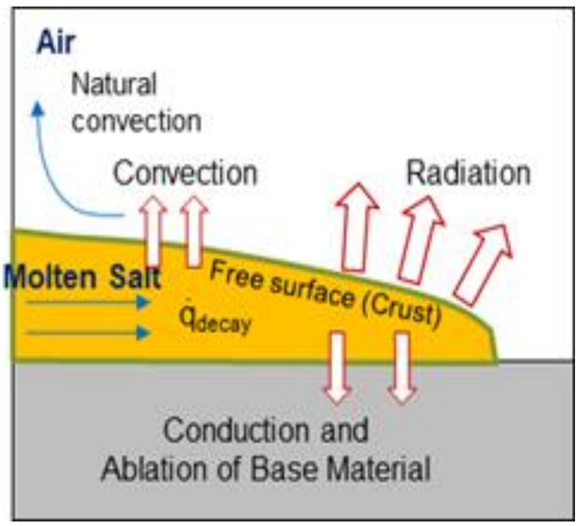

Fig. 1 Spreading and cooling concept of the spill molten salt.

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. The processes addressed include 1) molten salt spreading on stainless steel, 2) molten salt heat transfer (as a static pool and during spreading), and 3) molten salt splashing and aerosol generation.

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].

This study is focused on preliminary analysis on spreading distance of the spill molten salt as salt composition of KCl-NaCl-UCl_3 for marine MSR or KCl-UCl_3 for very small MSR using the ANSYS-Fluent computer code of CFD (Computational Fluid Dynamics) tool.

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. 2 shows ANSYS-Fluent input model for spreading analysis of the spill molten salt. Fig. 3 shows ANSYS-Fluent mesh for spreading of the spill molten salt.

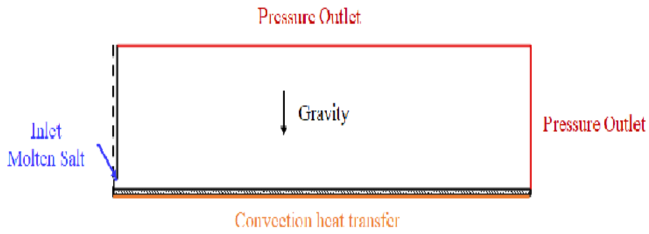

Fig. 2 ANSYS-Fluent input model for spreading analysis of the spill molten salt.

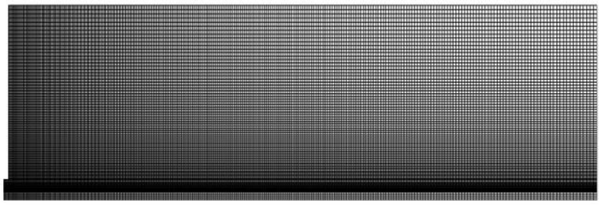

Fig. 3 ANSYS-Fluent mesh for spreading and cooling analysis of the spill molten salt.

In this study, the following conditions are used.

- Spill molten salt: KCl-NaCl-UCl_3(20.3-42.9-36.8 mol%) or KCl-UCl_3(47-53 mol%)
- Mass flow rate of spill molten salt: 0.1 kg/s for 20 sec or 120 sec
- Initial salt temperature: 923 K
- Solidification temperature: 743 K of KCl-NaCl-UCl_3 or 809 K of KCl-UCl_3
- Temperature of flat floor, atmosphere, and surrounding structures: 630 K
- Geometry: length 60 cm, height 15 cm
- Bottom plate thickness: 6.35 mm
- Number of mesh: 32,000
- Time step: 0.0002 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-NaCl-UCl_3 and KCl-UCl_3 in ANSYS-Fluent analysis. Solidification temperatures are different, but latent heat of fusion is same value because this value of KCl-UCl_3 is insufficient.

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

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

3. Results and Discussion

Preliminary analysis on spreading distance of the spill molten salt of KCl-NaCl-UCl_3 or KCl-UCl_3 in MSR was performed using the ANSYS-Fluent computer code. Figs. 4 and 5 show ANSYS-Fluent results on spreading distance and temperature distribution of the spill molten salt of KCl-NaCl-UCl_3 in case of 0.1 kg/s for 20 sec, respectively. The red color means liquid salt. Solidification of the molten salt changes color, as shown in Fig. 4. The spreading distance affects the temperature distribution. The spreading distance of spill molten salt of KCl-UCl_3 estimates as approximately 15.0 cm for 20 sec in condition with the mass flow rate of the spill molten salt of 0.1 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 17.7 cm at 120 sec.

Fig. 6 shows ANSYS-Fluent results on spreading distance of the spill molten salt (0.1 kg/s for 20 sec) with time increases as salt composition of KCl-UCl_3 or KCl-NaCl-UCl_3 in MSR. Fig. 7 shows ANSYS-Fluent results on spreading distance of the spill molten salt (0.1

kg/s for 120 sec) with time increases as salt composition of KCl-UCl_3 or KCl-NaCl-UCl_3 in MSR. The spreading distance of KCl-NaCl-UCl_3 is longer that of KCl-UCl_3, because the solidification temperature of KCl-UCl_3 is higher than that of KCl-NaCl-UCl_3. The superheat of spill molten salt is effective on the spreading distance. The spreading distance of 0.1 kg/s for 120 sec is longer that of 0.1 kg/s for 20 sec, because the spill molten salt is larger.

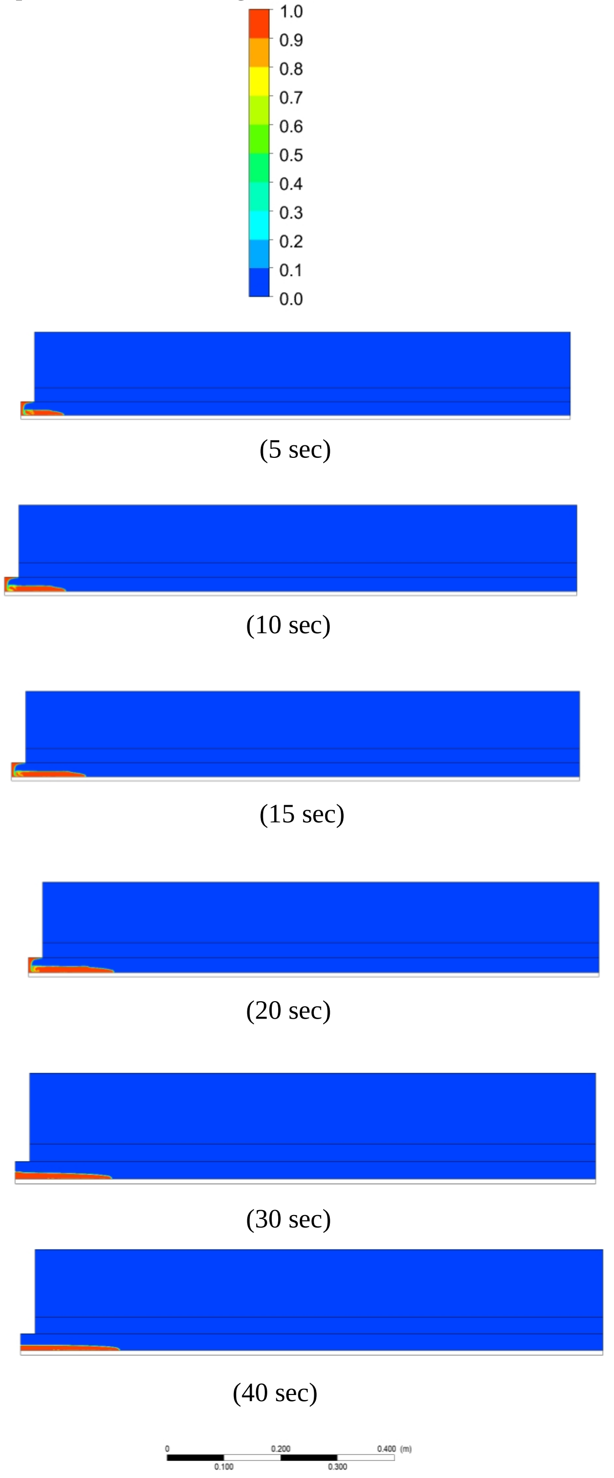

Fig. 4 ANSYS-Fluent results on spreading distance of the spill molten salt with time increase (KCl-NaCl-UCl_3).

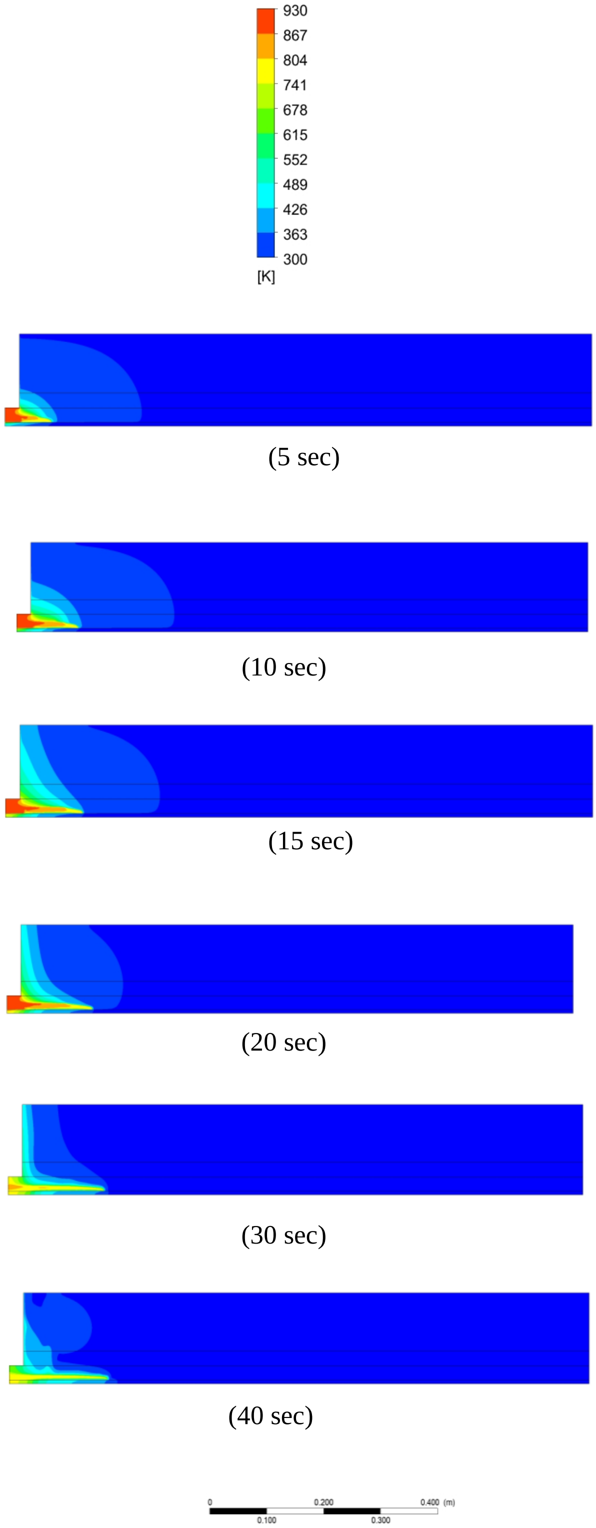

Fig. 5 ANSYS-Fluent results on temperature distribution of the spill molten salt with time increase (KCl-NaCl-UCl_3).

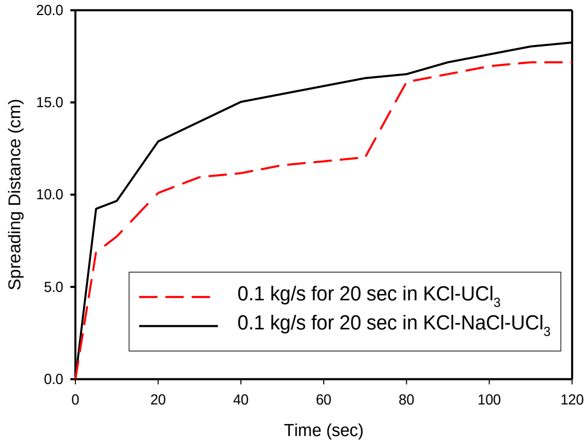

Fig. 6 ANSYS-Fluent results on spreading distance of the spill molten salt for 20 sec.

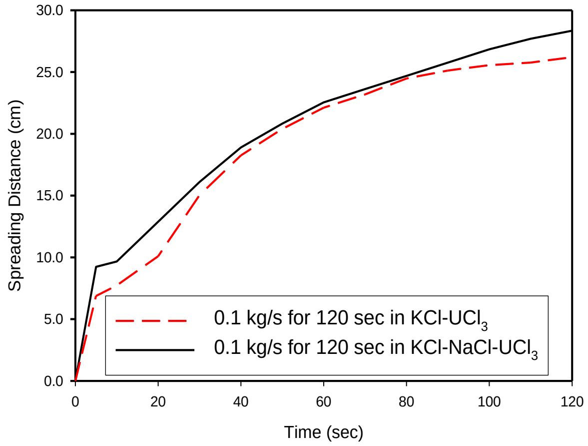

Fig. 7 ANSYS-Fluent results on spreading distance of the spill molten salt for 120 sec.

4. Conclusions

Preliminary analysis on spreading distance of the spill molten salt of $KCl-NaCl-UCl_3$ or $KCl-UCl_3$ in MSR has been performed using the ANSYS-Fluent computer code of CFD tool. Input model for ANSYS-Fluent analysis on spreading and cooling of the spill molten salt was developed. The spreading distance affects the temperature distribution. The spreading distance of spill molten salt of $KCl-UCl_3$ estimates as approximately 12.9 cm for 20 sec in condition with the mass flow rate of the spill molten salt of 0.1 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 s. Finally, the spreading distance of spill molten salt is 18.2 cm at 120 sec. The spreading distance of $KCl-NaCl-UCl_3$ is longer that of $KCl-UCl_3$, because the solidification temperature of $KCl-UCl_3$ is higher than that of $KCl-NaCl-UCl_3$. The superheat of spill molten salt is effective on the spreading distance. The spreading distance of 0.1 kg/s for 120 sec is longer that of 0.1 kg/s for 20 sec, because the spill molten salt is larger. More calculations for the spill molten salt are necessary to estimate effect of the main parameters, such as material properties, released mass, released time and spreading channel width. 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. If available, a verification study of present results will be performed.

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