Preliminary Analysis on Spreading and Heat Transfer Behavior of Molten Salt during the Salt Spill Accident

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1. Introduction

In recent years, molten salt reactors(MSRs) have been receiving lots of global attentions as a candidate of the safety-enhanced fourth generation small modular reactors(SMRs) [1]. This study was performed as a part of the researches for the development of marine MSR safety technology, which is one of the MSR R&D subprojects for marine propulsion and floating nuclear power plants. As with the severe accidents in typical light water reactors(LWRs), the salt spill accident is regarded as the maximum credible accident in MSR reactors and the thermohydraulic behavior of molten salt is of high importance for the evaluations of molten salt coolability, fission product behavior, and integrity of the reactor structures, and furthermore the development of accident mitigation measures and technology [2]. This is a preliminary study to select an analytic tool and establish the methodology for the investigations on the general thermohydraulic behavior of molten salt. ANSYS Fluent (2023 R2 version) was selected to investigate the general spreading and heat transfer behavior of molten salt. We performed Fluent CFD analysis on the FLiNaK salt behavior spilled onto a flat substrate, which has been investigated at Argonne National Lab(ANL) using MELTSPREAD code [2]. Same analytic conditions were applied to a two-dimensional axisymmetric model and the results were compared the MELTSPREAD analysis.

2. Analysis Model and Methods

2.1 Analysis Model

An analysis model of salt spill scenario is illustrated in Fig. 1 and the spill conditions are given in Table I, where two analysis cases were selected according to the considerations of time-dependent decay heat level shown in Fig. 2. Detailed FLiNaK thermophysical properties are given in the reference [2] and the constant values used in the ANL MELTSPREAD and CFD analyses as well are provided in Table 2. MELTSPREAD was developed at ANL specifically for ex-vessel core debris of LWRs to model the one-dimensional gravity-driven flow and freezing of molten material. In order to apply the same spill and boundary conditions used in MELTSPREAD analysis, an axisymmetric model with the dimensions of 500 mm × 156.35 mm having 56320 structured grids over the entire domain (air and substrate zones) was developed as shown in Fig. 3, where the boundary conditions are described.

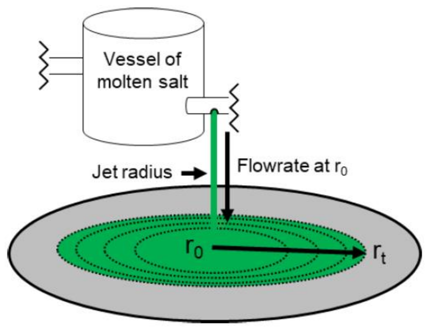


Fig. 1. Analysis model of spreading of molten salt spilled onto a flat substrate [2]

Table I: Spill conditions [2]

Spill condition	Value	
Initial salt temperature	650℃	
Total spill volume and corresponding mass	5 L 10.1 kg	
Volumetric flowrate and corresponding mass flowrate	12 L/hr 24.2 kg/hr	
Spill duration	25 minutes (1500 sec)	
Substrate material and thickness	Stainless steel 6.35 mm	
Radius of spill jet	5 mm	
Initial decay heat level (refer to Fig. 2)	12.38 kW/kg (25 MW/m^3)	
	Without (Case #1)	With (Case #2)

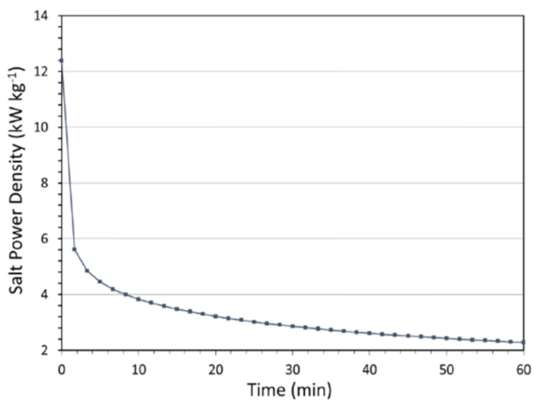


Fig. 2. Decay heat level in the salt [2]

Table II: FLiNaK thermophysical properties used in the MELSPTREAD and CFD analyses [2]

Property	Value
Liquid density	2020 kg/m^3
Solid density	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	3.99×10^5 J/kg
Surface tension	0.179 N/m
Radiation emissivity	1.0

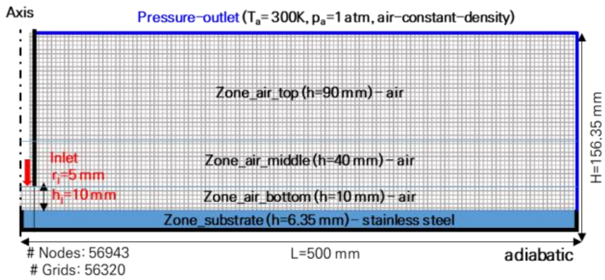


Fig. 3. Axisymmetric model and boundary conditions for CFD analysis

2.2 Analysis Methods

In order to meet the gravity-driven flow condition applied to the MELTSPREAD analysis, the falling height of the molten salt jet was minimized to 10 mm as shown in Fig. 3. Volume of fluid(VOF) and solidification & melting models were used to simulate the two phase flow created by cooling of molten salt, and the k-ε realizable model with standard wall function was set for the turbulent flow. In addition, discrete ordinate(DO) model was selected for the radiation heat transfer.

As shown in Table I, two base cases without(case #1) and with decay heat(case #2) were selected for the analysis, and transient analysis was performed for 1600 seconds(spill duration 25 minutes plus 100 sec) with 0.01 second time step. The user-defined function(UDF) of decay heat curve obtained from Fig. 2 was used for the case #2, in which the corresponding decay heat value is applied to the molten salt region where VOF is above 0.5.

3. Results

2.1 Fluent CFD Analysis

The time-varying spreading shapes of molten FLiNaK with the phase distribution (from blue-solid to red-liquid) are provided in Table III, and temperature distributions (from blue-300 K to red-930 K) in the entire domain are shown in Table IV. As the molten salt being spilled out of the nozzle onto the substrate and spreads away gradually, it cools down due to the heat transfer from the salt to the atmosphere and substrate. The melt solidification begins at the leading edge and the solid region expands gradually towards the axis. The evolution of spreading radius of molten salt between two cases is shown in Fig. 5, which shows clearly that the molten salt spreads further for the case #2 because the decay-induced heating retards the melt solidification and accordingly enhances the melt spreading to form a flatter shape.

Table III: Spreading shape and phase distribution

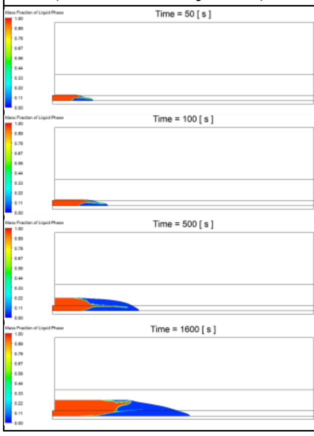
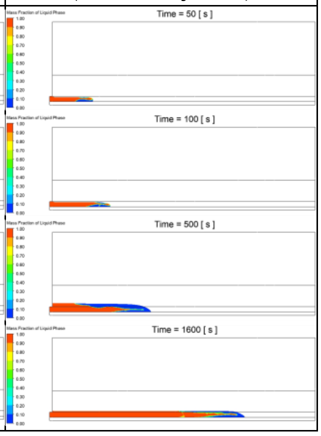
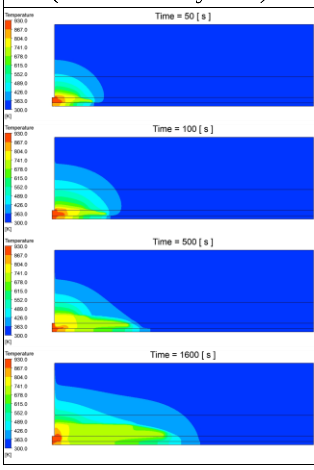
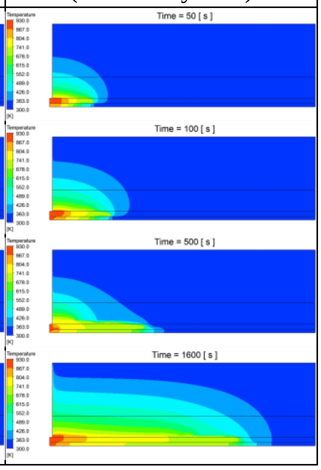
Case #1 (without decay heat)	Case #2 (with decay heat)
	

Table IV: Temperature distribution

Case #1 (without decay heat)	Case #2 (with decay heat)
	

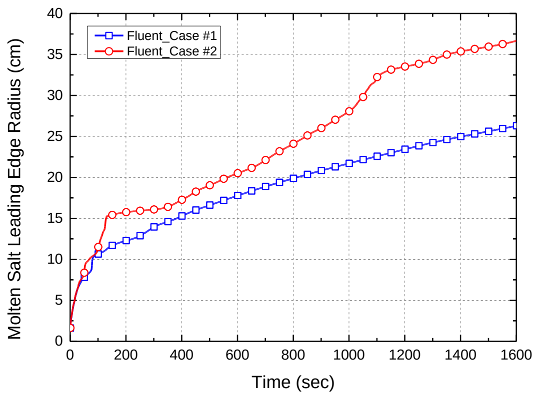


Fig. 4. Comparison of the spreading radius of molten FLiNaK

2.2 Comparison with MELTSPREAD Analysis

The predictions of spreading radius of molten salt for 100 seconds and final shapes at 1600 seconds between Fluent and MELTSPREAD analyses are compared in Figs. 4 and 5, respectively. Fluent predicts slightly faster spreading and gradual increase with time while the spreading radii by MELTSPREAD stop for both cases within tens of seconds because the leading edge freezes and forms a barrier to further spreading. As a result, the final shapes show big differences between them.

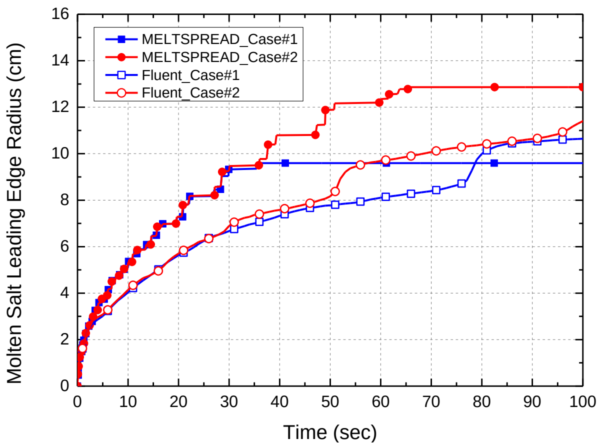
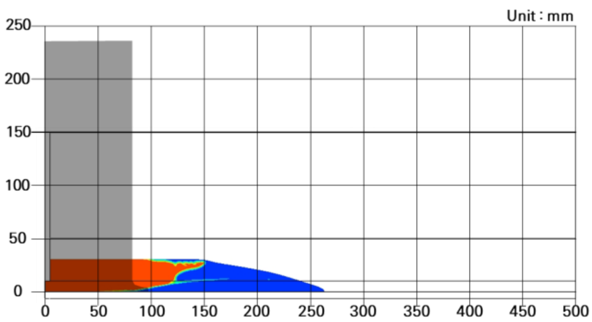
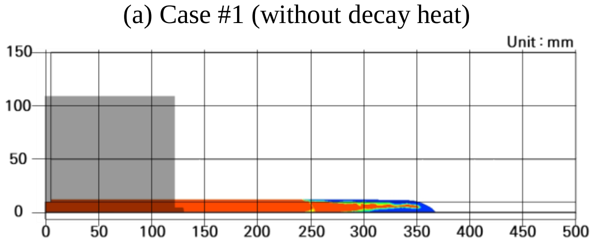


Fig. 4. Comparison of the spreading radius of molten FLiNaK between Fluent and MELTSPREAD analyses



(a) Case #1 (without decay heat)



(b) Case #2 (with decay heat)

Fig. 5. Comparison of final shapes of FLiNaK between Fluent(colored) and MELTSPREAD(grey) analyses

In addition, MELTSPREAD predicts much higher substrate temperatures at the location of *r*=10 cm for the case #2 as shown in Fig. 6, which is due to the anchoring of the leading edge near this location for long time. ANL has pointed out that the overall spreading area of the molten salt would be underestimated and the substrate heating would be overestimated for the case #2(with decay heat) in the current version MELTSPREAD due to the analysis limitation of re-melting of the solidified edge by decay-induced heating [2]. Therefore, it is believed that the Fluent CFD analysis of this study will provide more accurate results on the general spreading and heat transfer behavior of molten salt.

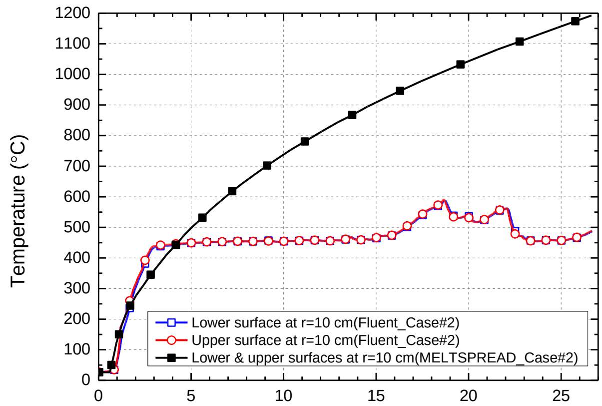


Fig. 6. Comparison of temperatures of the upper and lower surface of the substrate at the location of *r*=10 cm (case #2)

4. Conclusions

We performed a Fluent CFD analysis on the spreading and heat transfer behavior of FLiNaK molten salt spilled onto a flat substrate and investigated the effect of decay heat on the spreading behavior. Compared to the ANL MELTSPREAD analysis, the CFD results showed gradual spreading with time and larger spreading radius of the molten salt than MELTSPREAD. Due to some limitations in the current version of MELTSPREAD code, it is believed that the CFD analysis predicts the general spreading and heat transfer behavior of molten salt during the salt spill accident more accurately. Recently, NaCl-KCl-UCl_3 was selected as a fuel salt in the MSR R&D project and the design of the reactor systems is still in progress. Thus, further analysis will be performed in the future for the NaCl-KCl-UCl_3 salt by reflecting the geometric configurations of MSR systems.

ACKNOWLEDGMENTS

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[2] S. Thomas, J. Jackson, M. Farmer, Modeling Molten Salt Spreading and Heat Transfer using MELTSPREAD-Model Development Updates, ANL/CFCT-22/15, 2022.