Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Scaling analysis of melt spreading for MSR application

Jun-young Kang *, Sung Il Kim, Sang Mo An, Jun Ho Bae
Korea Atomic Energy Research Institute (KAERI), Daejeon, 34057, Rep. of Korea
**Corresponding author: kkang0602@kaeri.re.kr*

***Keywords :** Molten salt, melt spreading, scaling analysis

1. Introduction

The salt spill accident of a molten salt reactor (MSR) refers to the leakage of molten fuel salt along with a significant amount of radioactive material from the primary system. It is generally considered the maximum hypothetical accident in MSR, equivalent to a severe accident in conventional light-water reactors. [1]. Molten salt is flowed or is spread out on the catching pan or floor of containment shell and spreading of molten salt is major phenomena related to the stabilization of salt fuel or to design the safety function in MSR system. Existing researches about the spreading of molten salt have been reported with MELTSPREAD code [2] or computational fluid dynamics (CFD) [3]. However, their results show significantly difference and it is hard to identify an actual phenomenon because without any experiment for validation. Present study introduces scaling analysis of melt spreading for application of molten salt based on the analytical model.

2. Methods and Results

Melt spreading is complexed thermo-fluid process governed by 'hydrodynamic motion of spreading liquid' and 'solidification of melt during spreading' [4]. Flow regime is determined by flow velocity: gravity-inertia or gravity-viscous regime. Scaling analysis of melt spreading is based on the theory suggested T.N.Dinh et al of KTH [5].

2.1 Principle

Scaling is based on the two dimensionless parameters: dimensionless length (ratio between the average height of the spread melt and the capillary thickness) (Eq.1) and dimensionless time (ratio between the hydrodynamic spreading and the melt solidification) (Eq.2).

$$\bar{L} = \delta_{sp}/\delta_{cap} \quad (1)$$

$$\bar{T} = t_{conv}/t_{solid} \quad (2)$$

Dimensionless length is able to be measured by property and dimensionless time is function of process (total volume of melt, mass flux, melt superheat), geometry (width of spreading channel), boundary condition (convective heat transfer coefficient and ambient temperature) and property (heat of fusion, specific heat, density and viscosity of melt). Scaling map using two dimensionless parameters provides the guideline of the spreading length or required time for melt spreading.

In gravity-inertia regime, characteristic velocity U is derived by melt momentum equation function of spreading channel width and volumetric mass flow rate (Eq.3). On the other hands, velocity in gravity-viscous regime is assumed that spreading is largely driven by melt addition in the beginning of the spreading channel and is defined by Eq.4 [5]. Based on the spreading velocity, each flow regime has their own spreading time in Eq.5 and 6.

Solidification time of melt during spreading is derived by energy equation of melt and is used to determine the dimensionless time for scaling map. Solidification time is function of melt heat capacity, latent heat of melt, heat loss (upper and lower) and heat source (i.e., decay heat). Upward heat loss depends on the environment whether liquid coolant exists (i.e, wet-cavity) or not (i.e., dry-cavity) and it is related to the heat transfer mechanism by convection or radiation. Downward heat loss uses heat transfer coefficient by convection.

$$U_{inert} = \left(g \cdot \frac{G}{D}\right)^{1/3} \quad (3)$$

$$U_{visc} = \left(\frac{1}{3} g \cdot \frac{G^3}{\nu}\right)^{\frac{1}{8}} \left(\frac{G}{V_{tot}}\right)^{\frac{1}{2}} \quad (4)$$

$$t_{conv} = \frac{V_{tot}}{D \cdot \delta_{cap} \cdot U_{inert}} \quad (5)$$

$$t_{conv} \cong \frac{V_{tot}}{G} \quad (6)$$

$$t_{solid} = \delta_{cap}\rho_m \left(\frac{C_{p,m} \cdot \Delta T_{sup} + \eta H_{fusion}}{q_{up} + q_{dn} - q_v \delta_{cap}}\right) \quad (7)$$

$$\bar{L} = C\bar{T}^{0.5} \left(\frac{t_{conv,v}}{t_{conv}}\right)^{0.5} \left(\frac{\delta_v}{\delta_{cap}}\right)^{0.5} = C_v \bar{T}^{0.5} N^{0.5} \quad (8)$$

For one dimensional and viscid model of melt spreading is defined in Eq.8 and it is converted to inviscid flow model when viscous number N is below unity. Scaling analysis is able to be extended from one-dimensional channel to two-dimensional channel or open channel geometry.

2.2 Application

Result of MELTSPREAD code and CFD (FLUENT) calculation is evaluated to scaling map for melt spreading. Salt in target problem is FLiNaK (LiF-NaF-KF 46.5-11.5-42 mol%) and melt is spread on two-dimensional cylindrical geometry. Detailed information of domain and boundary condition is described in references [2,3]. Scaling map shows that melt thickness cannot be below the capillary thickness of melt and this indicates that the minimum values of dimensionless length is restricted by unity. Scaling map contains several models of melt spreading and target calculation is related to the open channel theory (OCT).

Compared to the FLUENT, MELTSPREAD shows dimensionless length (or thickness) significantly overestimated. Model of MELTSPREAD in the reference is bulk solidification which does not consider the crust layer in melt during spreading. Scaling model in the present study has also some uncertain parameters such as the part of heat loss and fitting constant for heat of fusion. However, scaling model suggests the guideline for spreading of molten salt and implies that CFD analysis is closer to the realistic situation than MELTSPREAD code. Also, experimental program about molten salt spreading is necessary to develop the computational code and to validate the code in the future.

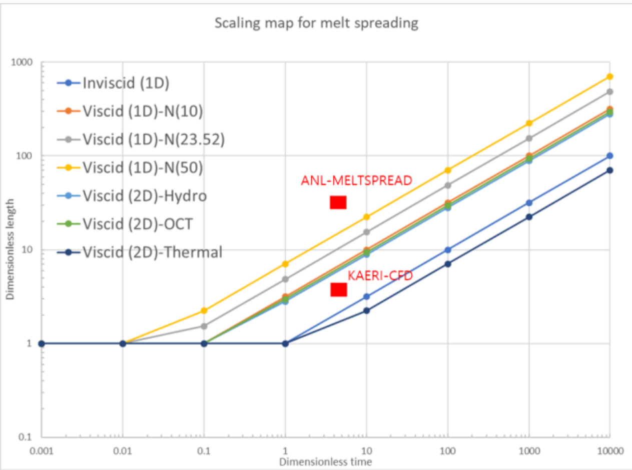

Fig. 1. Scaling map for melt spreading

3. Conclusions

Present study shows the results of scaling analysis for molten salt spreading and compares with the existing researches by MELTSPREAD and CFD for MSR application. MELTSPREAD in ANL is in progress to improve the model and apply the molten salt system. Also, domestic code for MSR application is required to cover the spreading phenomena related to safety analysis in the future.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2023-00261295).

REFERENCES

[1] B.Lee and S.I.Kim, Phenomena identification for accident condition of molten salt reactor, Transaction of the Korean nuclear society, spring meeting, Jeju, Korea, May 9-10, 2024

[2] S.Thomas and J.Jackson, Modeling molten salt spreading and heat transfer using MELTSPREAD-Model development updates, ANL/CFCT-22/15, 2022

[3] S.M.An and S.I.Kim, Preliminary analysis of spreading and heat transfer behavior of molten salt during the salt spill accident, Transaction of the Korean nuclear society, spring meeting, Jeju, Korea, May 9-10, 2024

[4] J.J.Foit and A.Veser, Similarity solutions, KATS experiments and CORFLOW results, Forschungszentrum Karlsruhe Technik und Umwelt (FZKA 6260), 1999

[5] T.N.Dinh et al., core melt spreading on a reactor containment floor, Progress in nuclear energy, Vol.36, No.4, pp.405-468, 2000