Preliminary Analysis on Spreading Distance and Time of Spill Molten Salt using Simple Analytical Model

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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 at 1,960 and 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 severe 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 fuel salt is very important for MSR safety. Fig. 1 shows spreading and cooling concept of the spill molten salt in an environment condition.

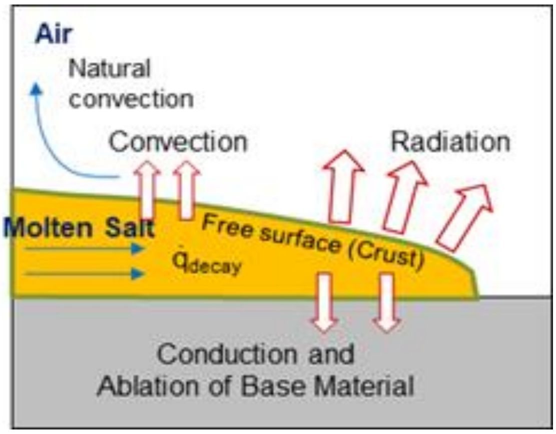

Fig. 1 Spreading and cooling concept of the spill molten salt.

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-UCl3) to highlight individual processes expected to affect the fate of spilled 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

The corium 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 in MSR. This is focused on preliminary comparison analysis on spreading distance and time of the spill molten salt in MSR with corium in PWR using a simple analytical model.

2. Simple Analytical Model on Melt Spreading

In a hydrodynamic aspect, the spreading of molten salt or corium depends on the gravitational, inertial, and viscous forces. In general, fluid spreading is divided into gravity and viscous regimes. In gravity-inertia regime, fluid spreading is not dependent on the viscosity. A simple model of melt or molten salt spreading is presented in this section. The reason for developing the model is to provide our own independent rationale for the real material spreading observations and the reported code-calculated spreading predictions. As part of the modeling effort a unique melt stopping criterion is introduced which departs significantly from the capillary thickness stopping criterion or from the somewhat arbitrary "fraction of heat of fusion to be removed during spreading" stopping criterion that have been used to interpret the results of experiments. In the model, the viscous melt retardation force is assumed small compared with the spreading melt inertia force.

The melt stopping criterion proposed here can be explained by referring to Fig. 2. This figure shows the spreading melt gravity current propagating forward over the substrate surface at the instantaneous speed U. Due to surface cooling by radiation the surface of the melt is solidifying and a crust of instantaneous thickness δ appears. The curst is regarded as unstable and subject to break off until it can grow fast enough at the leading edge of the current to form a frontal crust that prevents the melt from moving forward.

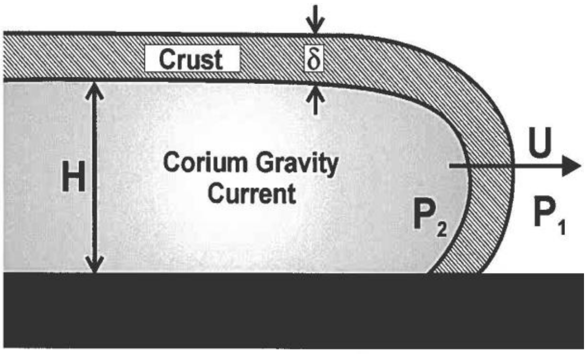

Fig. 2 Model of front of corium gravity current.

The driving pressure that forces the current forward is the average hydrostatic pressure over the depth H of the melt layer:

(1) $P_2 - P_1 = \frac{1}{2} \rho g H$

where ρ is the melt density, g is the gravitational constant and H is the spatially averaged instantaneous thickness of the melt layer behind the front. In writing this equation, the weight of the crust was ignored. Acting against the driving force is the force due to the elasticity of the crust cover, which to first order can be represented as

(2) $P_2 - P_1 \cong D/(H/2)^3$

where D is the crust stiffness given by Miles [7].

(3) $D = E\delta^3/12(1-\varepsilon^2)$

and H/2 in Eq. (2) is the radius of curvature of a cylindrically shaped gravity current front (see Fig. 2). In Eq. (3) E and ε are, respectively, the elastic modulus and Poisson's ratio of the crust material. Equating (2) and (3) gives

(4) $H_{el} = 2.0\ [E\delta^3/12(1-\varepsilon^2)\ \rho\ g]^{1/4}$

The term H_{el} designates the elastic thickness of the gravity current; it is analogous to the capillary thickness in the absence of a crust cover. The gravity current is assumed to stop flowing when the instantaneous thicknesses of the gravity current (H) and its crust cover (δ) satisfy Eq. (4). The crust is assumed to offer no resistance to the current as long as Eq. (4) is not satisfied. In order to simplify matters the motion of the gravity current is taken to be one-dimensional and a fixed quantity of cerium is assumed to be suddenly released to the corium catcher. For this case, the gravity current spreading law for an inviscid liquid is [8]

(5) $x = 1.6\ (gqt^2)^{1/3}$

where x is the distance the gravity current has traveled, t is the travel time and q is the volume of melt released per unit width of the spreading channel. The conservation of melt volume demands that

(6) $q = Hx$

The velocity U of the front is readily obtained by differentiating Eq. (5) with respect to time to get

(7) $U = 1.067\ (gq/t)^{1/3}$

Eliminating x between Eqs. (5) and (6) gives the relationship between the thickness of the current and time

(8) $H = 0.625(q^2/gt^2)^{1/3}$

The thickness δ of the crust at the front of the gravity current is obtained by making the justifiable assumption that the rate of crust growth is limited only by the rate of radiation heat loss off the surface evaluated at an effective solidification point T_{mp} of the melt material:

(9) $h_{fs}\delta = \varepsilon_r \sigma T^4_{mp} \tau$

where h_{fs} is the latent heat of fusion of the melt material, ε_r is the emissivity of the crust surface and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2 K^4). Equation (9) is an energy balance that equates the latent heat released by the superficial freezing of the front's surface with the radiation heat loss over the time period τ, where τ is identified with the residence time of a surface segment of melt at the front. For the tank-track-like motion at the cylindrical front we may write

(10) $U\tau = \frac{\pi}{2} H$

Solving Eq. (9) for δ and using Eq. (10) for τ gives

(11) $\delta = (\varepsilon_r \sigma T^4_{mp})(\boldsymbol{\pi} H/2U)/(\rho h_{fs})$

Eliminating t between Eqs. (5) and (7) results in

(12) $U = 1.35(gq/x)^{1/2}$

By substituting H from Eq. (6) and U from Eq. (12) into Eq. (11) yields

(13) $\delta = 1.16(\varepsilon_r \sigma T^4_{mp})\ (q/gx)^{1/2}/(\rho h_{fs})$

Identifying δ from the above equation with δ in Eq. (4) and identifying H from Eq. (6) with H_{e1} in Eq. (4) gives, after some algebraic steps, the desired equation for the melt spreading distant x_{sp}

(14) $x_{sp} = 0.746\ q\ [(1 - \varepsilon^2)\rho g/E]^{2/5}$
$[(\rho h_{fs} g^{1/2})/(\varepsilon_r \sigma T^4_{mp})]^{6/5}$

The time t_{sp} for the melt to spread over this distance is, from Eq. (5),

(15) $t_{sp} = 0.494(X_{sp}^3/(gq))^{1/2}$

3. Results and Discussion

Preliminary analysis on spreading distance and time of the spill molten salt in MSR to compare with the corium in PWR was performed using the simple analytical model. Table I shows the input parameters and calculation results for spreading distance and time. Spreading distance and time were calculated using equations (14) and (15).

Table I: Input parameters and calculation results for spreading distance and time.

	Corium	Molten Salt
Composition	UO_2, ZrO_2	$NaCl$ - $MgCl_2$ - UCl_3
Liquid Mass (kg), Volume (m^3)	210, 0.03	210, 0.0629
Channel Width(m)	0.4	0.4
ρ (density, kg/m^3)	7,000	3,338
Specific Heat (J/kg.K)	533.2	704.2
q (liquid volume /unit width, m^2)	0.075	0.157
T_{mp}(solidification temp., K)	2200	793
ξ (Poission's ration)	0.3	0.3
E (elastic modulus, Pa)	0.8×10^{11}	0.8×10^{11}
ξ_r (emissivity)	0.8	0.95
h_{fs} (latent heat of fusion, J/kg)	3.0×10^5	1.44657×10^5
σ (Stefan-Boltzmann constant, $W/m^2.K^4$)	5.67×10^{-8}	5.67×10^{-8}
g (gravitational constant, m/s^2)	9.8	9.8
x_{sp} (spreading distance, m)	5.5	2.3
t_{sp} (spreading time, sec)	7.5	1.4

In general, the spreading distance and time of the molten salt are shorter than those of the corium spreading, because of the material properties. The spreading is restricted by inertia due to a low viscosity and a high released rate of the spill molten salt or the corium, that is, gravity-inertia spreading regime.

4. Conclusions

Preliminary analysis on spreading of the spill molten salt for the MSR was performed using the simple analytical model, which was compared with the corium for the PWR. The spreading time and distance of the molten salt was analyzed. The spreading distance and time of the molten salt are shorter than those of the corium spreading, because of the material properties. 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 spilled molten salt including complex heat transfer is necessary to verify the present results.

ACKNOWLEDGEMENT

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