Sensitivity Analysis of Phase Change Models for Ex-vessel Core Melt Spreading

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***Keywords : CFD, Ex-vessel corium spreading, VULCANO VE-U7 test, Phase change model**

1. Introduction

In the severe accident safety research of light water reactors, the spreading behavior of ex-vessel core melt is considered as an important phenomenon for the investigation of the melt coolability and molten core-concrete interaction (MCCI). During the past a few decades, a number of numerical [1-8] and experimental studies of the ex-vessel core melt spreading such as VULCANO [9] and FARO [10] using prototypic corium have been performed and some analysis codes such as MELTSPREAD (1D), THEMA (2D), LAVA (2D), THERMOS-MSPREAD (2D) and CORFLOW (3D) have been developed. Similarly, the spreading behavior of molten salt in the salt spill accident is also a key topic to be addressed in the molten salt reactor (MSR) safety research [11]. In our previous study [12], CFD simulations of the FLiNaK molten salt spreading were performed and the results of transient salt spreading behavior showed relatively large differences from the MELTSPREAD code analysis [11]. Also, it was found that the freezing of the molten salt leading edge plays a barrier to block further spreading and accordingly has a significant influence on the salt spreadability. However, the experimental results for the validations of those CFD and code analyses are still unavailable. Therefore, the objectives of this study are to check the validity of the CFD methodology in the previous work [12] to estimate the experimental results of the ex-vessel core melt spreading behavior and to investigate the phase change models to consider the effect of melt solidification on the melt spreadability.

2. Numerical Simulation for Validation

2.1 Ex-vessel Core Melt Spreading Test

The VULCANO VE-U7 [9] using prototypic molten corium was selected as the ex-vessel core melt spreading tests for the CFD validation. The corium consists of UO_2 (61 wt.%), ZrO_2 (30 wt.%) and other oxides, which has a liquidus and solidus temperatures of 2623±50 K and 1273±75 K, respectively. The 40.8 kg of corium at 2450±80 K was poured at a flow rate of 4.3 kg/s, and then enters the spreading section which is divided into two symmetrical channels made of ceramic (zirconia bricks) and siliceous concrete substrates (Fig. 1). The corium spread at almost the same velocity for 7.7 seconds. The measured corium mass, corresponding volume and spreading distance from the end of the stabilization pool after stopping the melt spreading were 14 kg (2.8 L) and 45.5 cm over the ceramic substrate and 12.6 kg (2.4 L) and 36 cm over the concrete substrate. Based on the measured mass and volume at each channel, the corium densities were estimated to be 4940 kg/m^3 and 5180 kg/m^3 over ceramic and concrete substrates, respectively.

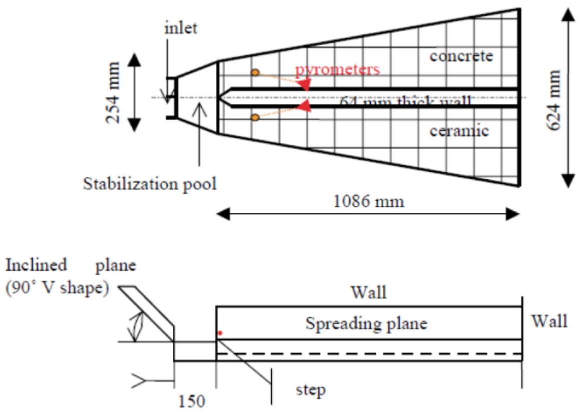

Fig. 1. Test channels of VULCANO VE-U7 test [4]

2.2 Numerical Methods

The VULCANO VE-U7 test only over the concrete channel was simulated using ANSYS Fluent (2024 R1). The simulation models and solving options were basically set identically to those used in the previous work [12] to check the validity of the CFD methodology. Volume of fluid (VOF) were adopted for the unsteady liquid-gas flow behavior. The geometric reconstruction scheme was applied for the interface (free surface) tracking, which assumes a piece-wise linear shape of the interface based on the volume fractions of the two phases. The k-ε realizable model with standard wall function was applied for the convection-induced turbulent flow in the gas phase. Discrete ordinate method (DOM) was selected for the radiative heat transfer calculations, where the number of angles discretized was set to 5 both in the polar and azimuthal directions. The absorption coefficients determining the exponential attenuation of the radiation intensity were set to 10^4 m^{-1} for corium and 0 m^{-1} for gas (transparent). Two representative fixed grid phase change models were used to investigate the corium solidification effects on the spreading process. One is an enthalpy-porosity technique adopted in ANSYS Fluent, where the mushy zone parameter A_{mush} measures the amplitude of the damping of the liquid-solid mixture flow, and the higher this value the steeper the transition of the velocity of the material to zero as it solidifies [13]. The other is temperature-dependent viscosity model, which will be described in the following section in detail. The sensitivity analyses depending on the A_{mush} and corium viscosity values were performed in this study.

2.3 Physical Properties of Corium

Table 1 lists the physical properties of corium used in Ye et al. [3] and this study as well, where the corium decay heat was not considered in this study and the latent heat of fusion value was taken from Yeon et al. [2]. Among the properties, the corium viscosity has the most significant influence on the spreading behavior, and the temperature-dependent viscosity curve based on the Ramaccioti's corium viscosity model [1, 14] was used as one option for the sensitivity analysis.

Table I: Physical Properties of Corium [3]

Property	Value
Density	5180 kg/m^3
Surface tension	0.5 N/m
Emissivity	0.8
Viscosity	Fig. 2
Specific heat (C_p)	Fig. 2
Thermal conductivity	3 W/m·K
Latent heat of fusion	3.62×10^5 J/kg [2]
Contact angle	80°

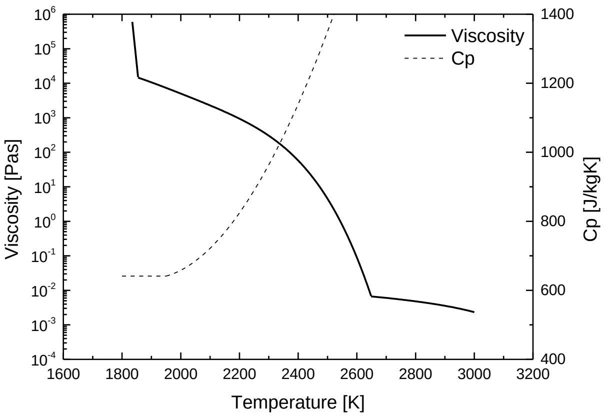

Fig. 2. Temperature-dependent dynamic viscosity and specific heat of corium [3]

The physical properties of nitrogen were used as those of the gas phase, in which the density was calculated as that of an incompressible ideal gas, and the other properties (specific heat, viscosity, conductivity) as functions of temperature.

2.4 Geometry and Boundary Conditions of Computational Domain

The concrete channel of the two symmetric channels was considered based on the previous work by Ye et al. [3], and the geometry of the computational domain with boundary conditions was constructed as shown in Fig. 3. The channel inlet and outlet dimensions are 95 mm by 65 mm and 280 mm by 100 mm, respectively. The volume was initially filled with gas (nitrogen) at 300 K, and corium at 2450 K enters the concrete channel at the constant velocity of 0.0503 m/s for 7.83 seconds, which corresponds to the time duration when total 12.6 kg of corium having 5180 kg/m^3 density enters the channel at 0.0503 m/s.

The conductivity and thickness of the concrete wall at the bottom were set to 50 W/m·K and 0.2 m, respectively in order to reflect the average conductive heat loss of about 500 kW/m^2 from the corium to the bottom wall. The constant temperature at 323 K was applied at the bottom, top, end and side walls while the adiabatic at the center, front and end walls. The convection with 5 W/m^{2}K was applied at the side wall and radiation heat transfer at top and end walls. The pressure-outlet condition allowing gas backflow at 323 K was applied at the outlet.

The domain was discretized with 99000 hexahedral cells. For the transient simulations, an explicit time discretization was used with a fixed time step of 0.001 s for total 30 seconds.

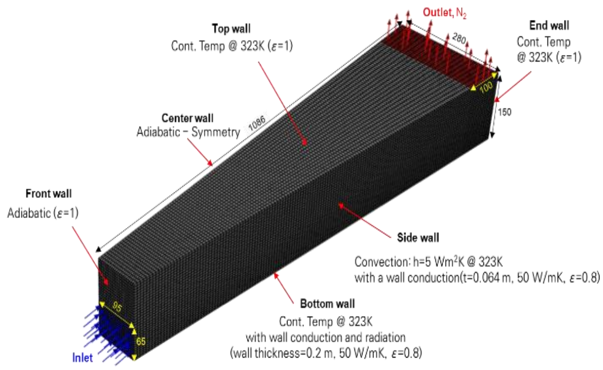

Fig. 3. Geometry and boundary conditions of the computational domain

2.5 Simulation Cases for Sensitivity Analysis

The mushy zone parameter A_{mush} value with the solidus and liquidus temperatures can be specified only when the solidification & melting model (i.e., enthalpy-porosity technique) is activated in Fluent, while the corium viscosity value can be set regardless of the use of the solidification & melting model. Table II was set according to the combinations of those two sensitivity parameters (A_{mush} and corium viscosity values), where the viscosity values of 18.6 Pa·s and 0.006675 Pa·s corresponds to the viscosity at the corium inlet temperature of 2450 K and liquidus temperature of 2623 K, respectively. Cases 1 and 3 are the combinations of the melt solidification (default value of A_{mush} =10^5 kg/(m^{3}s)) and temperature-dependent viscosity models. Cases 2 and 4 are for the separate effect of the viscosity without melt solidification, which are the same conditions with 'Case 1' and 'Case 4A', respectively in Ye et al. [3]. Cases 5, 6 and 7 are for the separate effect of A_{mush} (i.e., melt solidification) with the constant viscosity at liquidus temperature.

Table II: Simulation Cases

Case	A_{mush} [kg/(m^{3}s)]	Viscosity [Pa·s]	Remarks
1	10^5	Fig. 2	O
2	N/A	Fig. 2	Case 1 in [3]
3	10^5	18.6	O
4	N/A	18.6	Case 4A in [3]
5	10^6	0.006675	O
6	10^7	0.006675	O
7	10^8	0.006675	O

3. Results and Discussion

3.1 Simulation Results

Fig. 4 shows typical simulation results of three-dimensional corium spreading behavior at selected times and two-dimensional contours of melt volume fraction (0-blue to 1-red), solidified melt mass fraction (0-blue to 1-red) and temperature (300 K-blue to 2500 K-red) at the mid plane between the center and side walls.

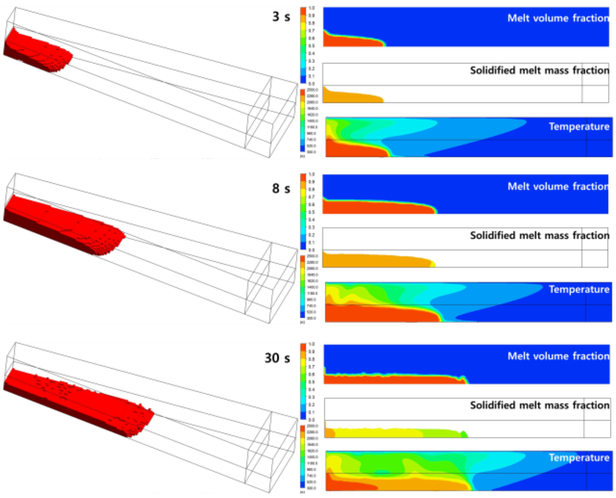

Fig. 4. Simulation results for Case 1.

Fig. 5 presents the evolution of spreading distances from the channel inlet and comparisons with the VOLCANO VE-U7 experiments. The melt spreading in the test stopped at around 8 seconds near the end of melt injection into the channel, while all the simulations estimated continuous but slower spreading after that time. The time-variation of spreading distances of Cases 1 and 2, and Cases 3 and 4 were almost the same from each other, and the Cases 1 and 2 showed better agreement with the test results in the early phase before 8 seconds. That is, the melt solidification model with the A_{mush}=10^5 value did not have a significant effect on the general spreading behavior. Instead, the corium spreading was retarded very effectively by the dramatic increase of corium viscosity resulting from cooling, and consequently VOLCANO VE-U7 test results were predicted well with the temperature-dependent viscosity model shown in Fig. 2. Therefore, as reported in the previous studies [1-7], the Ramaccioti's temperature-dependent viscosity model was found very effective to estimate the overall corium spreading behavior. However, there is a limitation that the melt solidification cannot be considered as in reality when using only the viscosity model.

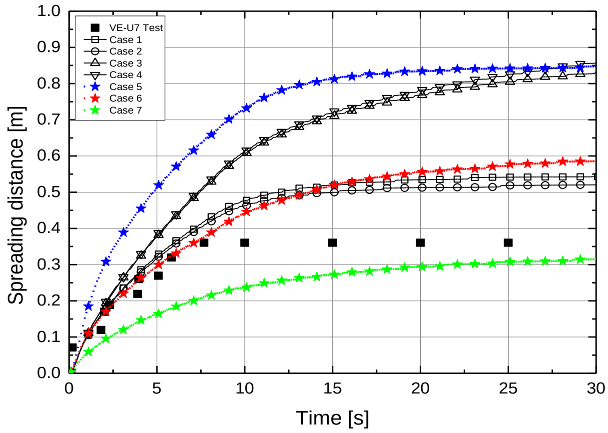

Fig. 5. Evolution of corium progression

On the other hand, it was also possible to predict the test results appropriately using the corium solidification model by adjusting the A_{mush} value with the constant viscosity of 0.006675 Pa·s at liquidus temperature (i.e., without using the temperature-dependent viscosity model). As shown in Fig. 5, the corium spreading behavior showed large differences between the A_{mush} values of 10^6 (Case 5), 10^7 (Case 6) and 10^8 (Case 7); the higher this value the slower the melt spreading due to higher damping of the liquid-solid mixture flow. As a result, the Case 6 showed the best agreement with the experiments in the early phase before 8 seconds not only among the three cases but all the simulation cases. This means the corium spreading behavior can be simply predicted using the melt solidification model with a proper value of A_{mush}, and thus the challenging work for obtaining the delicate temperature-dependent models for various melt compositions is not needed. Nevertheless, it is still necessary to investigate the proper A_{mush} values for various melts.

3.2 Comparison with Previous Studies

Fig. 6 shows the comparisons of some simulation results in this study from 0 to 10 seconds with the previous results by Ye et al. [3] and Zacha and Zelezny [4]. The simulation results of Cases 2 and 4 corresponding to the same conditions of 'Case 1' and 'Case 4A', respectively in [3] agreed exactly with each other. Thus, it was confirmed this study reproduced the

CFD results of [3] very well. 'Case 4C' is the case using constant corium viscosity of 100 Pa·s. The Case 6 in this study and 'c-150-rad' (use of DOM radiation model with 150 W/m·K for the bottom concrete conductivity) in [4] showed nearly the same and good agreements with the test results. The 'Case 4C' in [3] showed slightly slower spreading than Case 6 and 'c-150-rad' but the best agreement among all the cases compared in Fig. 6.

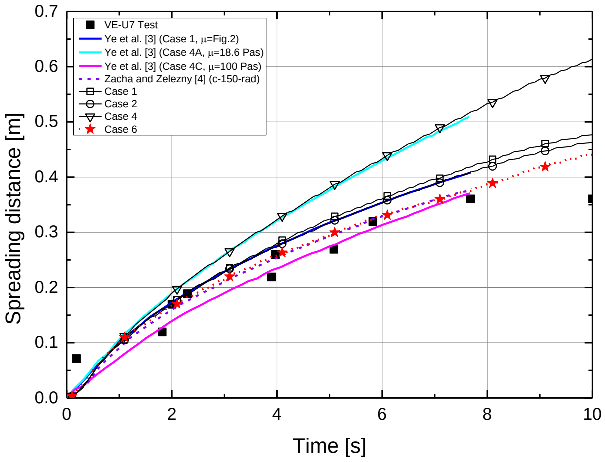

Fig. 6. Comparison with previous studies

4. Conclusions

We performed the CFD simulations of VOLCANO VE-U7 ex-vessel core melt experiment using ANSYS Fluent and investigated the melt solidification effect on the melt spreading behavior. In order to reflect the melt solidification, the two methods were considered. One is a typical method in the many corium spreading studies to use the melt viscosity models (constant values from 0.006675 to 100 Pa·s or Rammaccioti's temperature-dependent viscosity model) without the melt solidification. The other is adopted in this study to use only the melt solidification model in Fluent by adjusting the mushy zone parameter between 10^5 and 10^8 kg/(m^{3}s) with the constant viscosity at the liquidus temperature (0.006675 Pa·s). The simulation result of the latter method with the mushy zone parameter of 10^7 kg/(m^{3}s) showed satisfactory agreement with the VOLCANO VE-U7 test. Therefore, it is believed that the general spreading behavior for various melts can be predicted without the temperature-dependent model. However, there might be an optimum value of the mushy zone parameter for a melt composition, so it is necessary to investigate the various spreading tests with the different melt compositions. Moreover, the CFD methodology established from this study will be applied to the molten salt spreading analysis for the MSR development.

ACKNOWLEDGMENTS

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

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