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Experimental and numerical study of stratification and solidification/melting behaviors

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HIGHLIGHTS

- Numerical analysis of stratification and solidification/melting behaviors.
- Validation experiment performed with low-melting-point materials.
- Investigation of layer configurations and heat transfer characteristics.
- Good agreement between the calculation and experimental results.

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ABSTRACT

Given the severe accident of a light water reactor (LWR), stratification and solidification/melting are important phenomena in melt corium behavior within the reactor lower head, influencing the decay heat distribution and ablation of penetration tube and vessel wall. Numerical calculation is a necessary and effective approach for mechanistic study of local melt corium behavior. In this study, the improved moving particle semi-implicit (MPS) method was applied for investigating the stratification and solidification/melting phenomena. The implicit viscous term calculation technique and stability improvement technique were adopted to enable MPS to simulate the stratification process of materials with high viscosity in phase transition stage. The solid–liquid phase transition model was also coupled with MPS method. The validation experiment was carried out with low-melting-point metal tin and NeoSK-SALT. The layer configurations and temperature profiles obtained from MPS calculation showed good agreement with the experimental results. Meanwhile, the calculation results indicated that the material freezing behavior could affect the layer formation, and the layer configurations also significantly influenced the temperature profiles and heat flux distributions. The present results demonstrated that MPS method has the capacity to understand the local melt behavior in detail that is relevant to stratification and phase transition.

1. Introduction

Stratification and solidification/melting are common multiphase phenomena; occurring in nature and industrial processes; which are also of great significance in nuclear reactor safety analysis that involves severe accident scenarios. In boiling water reactor (BWR); large cavity below the reactor pressure vessel (RPV) disables external cooling of RPV by water flooding. After the residual water boils off at the late in-vessel stage; the quenched debris as well as the intact fuel pellets starts melting and probably forms a molten pool in the lower head of RPV due to self-heating by decay heat. The interactions between metallic and oxidic materials are complicated. The eutectic and chemical reactions could take place among two or more kinds of materials; and the separated melt layers could present following the phase equilibrium of metallic and oxide materials.

The MASCA program (Asmolov et al., 2001, 2003, 2004, 2007, 2008; Tsurikov et al., 2007) has experimentally investigated the chemical behavior of reactor core material mixtures containing oxidic and metallic components. The results demonstrated that uranium as well as zirconium could be extracted from oxide phase into metallic phase by steel, influenced by steel concentration and oxygen potential in the system; therefore three-layer configuration with a heavy metal layer at the bottom could form. It also expanded the database of nuclear material properties, such as density, liquidus temperature and viscosity of corium as well as the

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corium purity, which significantly affected the melt behavior in reactor lower head. SIMECO experiment (Theerthan et al., 2001; Sehgal, 2004) investigated natural convection in multi-layered liquid pools with volumetric heat generation in one or more layers. The results were obtained concerning heat flux distribution and the split of heat generation in upward and downward directions. The LIVE-L6 (Palagin et al., 2012) was carried out to investigate the thermal-hydraulic behavior of a stratified melt pool in the reactor vessel lower head. In the experiment the molten pool using KNO_3–$NaNO_3$ as the simulant corium was separated into two parts by a copper plate. The results described the temperature profiles in two melt pool layers and the heat flux distributions at the vessel wall, determining heat removal from melt corium and in-vessel melt retention.

Ozrin et al. (2010) constructed a thermodynamic model of O–U–Zr–Fe system based on MASCA data and other available experimental results to quantitatively simulate the interaction between liquid oxidic corium and steel. The model described the immiscibility of the oxide and metal phases of the core melt corium and made it possible to estimate their densities that determined the layer configuration. Fukasawa and Tamura (2007) performed thermodynamic equilibrium calculation of stratified melt corium with the database that was developed for corium U–Zr–Fe–O–B–C–FPs system using the ionic two-sublattice model. The stratification scenario and material composition in each layer predicted by the model agreed with the MASCA test. Concerning the thermal-hydraulic behavior in reactor lower head, MAAP (Suh and Henry, 1996a,b) and MELCOR (Gauntt et al., 2005) system codes assumed melt pool to separate into two or three layers. The heat transfer characteristics between layers and melt corium and vessel wall were calculated with empirical correlations. PECM (Tran and Dinh, 2009a,b) that adopted effective thermal conductivity to represent the turbulent convection in melt pool was capable to predict the temperature profile in each layer and heat flux distribution surrounding the melt pool.

Forming corium layers influences the distribution of decay heat and heat transfer in the lower head, and consequently determines the failure way of vessel wall and penetrations. To date, however, little research could be found which focuses on the simultaneous stratification and phase transition in the transient process. That is a probable phenomenon of melt behavior in lower head, for example the structural material could be ablated by melt corium, and then the liquid metallic material form the top layer. Since experimental method is very limited under many conditions, and since conventional numerical methods have difficulties in capturing fluid interface and free surface, applying a new numerical method not relying on empirical correlations is necessary for mechanistic melt behavior study in the reactor lower head.

The moving particle semi-implicit (MPS) (Koshizuka and Oka, 1996) method is one of particle methods for analyzing incompressible mediums such as water and solid not using grid mesh. MPS method has been widely applied in free surface and multiphase flow, such as breaking waves (Koshizuka et al., 1998) and droplet breakup behavior (Nomura et al., 2001). MPS-MAFL (Yoon et al., 1999), a hybrid method, was also developed, which predicted heat transfer of pool boiling successfully without relying on empirical correlation (Yoon et al., 2001). It was also applied for analyzing rising bubble in a stagnant liquid pool (Chen et al., 2011; Ikejiri et al., 2007).

In the severe accident study of a reactor, the MPS method is an effective and robust approach for detailed analysis of physical scenarios. It has been used for fuel–coolant interaction (Ikeda et al., 2001), vapor explosion (Koshizuka et al., 1999), and ex-vessel molten corium spreading (Kawahara and Oka, 2012), taking place in terms of severe accidents of light water reactor (LWR). Complex phenomena in hypothetical core disruptive accident of sodium-cooled fast reactor were also investigated using MPS method (Uehara et al., 2009; Morita et al., 2011). It is expected, therefore, that the MPS method is also applicable for mechanistic study of local melt behavior in RPV lower head of a LWR after the pressure vessel dries out. In our previous study, the validation of MPS code on stratification behavior analysis without heat transfer and phase transition has been performed (Li et al., 2013).

In the present study, stratification and solidification/melting behaviors in multiphase flow were numerically analyzed with the improved MPS method. The implicit viscous term calculation technique and stability improvement technique were adopted. The solid–liquid phase transition model was also coupled with MPS method. The validation experiment was performed with low-melting-point metal tin and NeoSK-SALT. The time histories of layer configurations and temperature profiles obtained from calculation were compared with experimental results.

2. Numerical modeling

2.1. Basic MPS method

The governing equations are mass, momentum and energy conservation equations:

$$\frac{D\rho}{Dt} = 0 \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \mathbf{F} \tag{2}$$

$$\frac{Dh}{Dt} = k\nabla^2 T + Q \tag{3}$$

where ρ, t, $\mathbf{u}$, P, ν, $\mathbf{F}$, h, k, T and Q are fluid density, time, velocity vector, pressure, kinematic viscosity, external force, enthalpy, thermal conductivity, temperature and heat source, respectively. In MPS method, the advection terms are directly incorporated into the calculation by moving particles. All the differential operators in the governing equations should be substituted by the following particle interaction models.

A common kernel function applied for discretizing differential operators is described as:

$$w(r) = \begin{cases} \dfrac{r_e}{r} - 1 & 0 \le r < r_e \\ 0 & r_e \le r \end{cases} \tag{4}$$

where r_e is the cutoff radius used for limiting the interactions, and r is the distance between two particles. Particle number density of particle i at the position $\mathbf{r}_i$ is defined as the summation of weight functions:

$$n_i = \sum_{j \ne i} w(|\mathbf{r}_j - \mathbf{r}_i|) \tag{5}$$

The fluid density is proportional to the particle number density. For the incompressible fluid, the standard value n^0 evaluated at the initial particle configuration is used to substitute n_i in calculation.

Gradient operator of an arbitrary scalar quantity φ is the local weighted average of gradient vectors between particle i and its neighboring particles within r_e

$$\langle \nabla\varphi \rangle_i = \frac{d}{n^0}\sum_{j \ne i} \frac{\varphi_j - \hat{\varphi}_i}{\left|\mathbf{r}_j - \mathbf{r}_i\right|^2}(\mathbf{r}_j - \mathbf{r}_i)w(|\mathbf{r}_j - \mathbf{r}_i|) \tag{6}$$

where d is the number of spatial dimensions. Laplacian operator is interpreted as a diffusion process of φ to neighboring particles:

$$\langle \nabla^2\varphi \rangle_i = \frac{2d}{\lambda n^0}\sum_{j \ne i}(\varphi_j - \varphi_i)w(|\mathbf{r}_j - \mathbf{r}_i|) \tag{7}$$