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Numerical investigation of erosion and heat transfer characteristics of molten jet impinging onto solid plate with MPS–LES method

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ABSTRACT

Erosion of solid structure and lower head vessel wall by molten jet impingement is a common and important phenomenon in nuclear reactor severe accident. In the present study, a numerical simulation platform was constructed using MPS method with large eddy simulation, and was validated against the experiments that were performed using molten NaCl and Tin as the impingement jet, respectively, and using Tin plate as the target structure. The simulated time-dependent erosion depth agreed well with the experimental data, and the detailed configurations of the crust and molten film formed at the interface of molten jet and plate were reproduced. Furthermore, a parametric study of the effects of molten jet velocity, diameter and temperature on the erosion behavior and heat transfer characteristics was carried out. The results showed that the erosion depth increased as the increase of molten jet velocity, but when the jet velocity was too small, the melt pool formed in the eroded cavity could delay the erosion significantly. The molten jet with a large diameter delayed the erosion due to the thick melt layer in the eroded cavity. The high molten jet temperature resulted in a fast erosion of plate, but the existence of crust in NaCl–Tin delayed the erosion compared with Tin–Tin where no crust formed. Heat transfer coefficient at the eroded plate surface decreased as the erosion depth increasing, due to the development of crust and molten film. It increased with the increase of molten jet velocity and temperature, but decreased as the increase of molten jet diameter.

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1. Introduction

Fukushima Daiichi nuclear disaster is another nuclear severe accident following TMI-2 and Chernobyl accidents. From the lessons learned from Fukushima Daiichi nuclear severe accident, we could find that people have not clearly understood the severe accident progression and the phenomena mechanisms. That is why we don't know what exactly happened in Fukushima Daiichi Units 1–3 and the current status of the reactors, which brought many difficulties to Tokyo Electricity Power Company (TEPCO) to decommission the damaged reactors. The Fukushima Daiichi nuclear severe accident pronounces that further research on nuclear severe accident is a pressing need to enhance nuclear safety and to establish severe accident management guidelines (SAMGs) for nuclear power plants (NPPs). In the nuclear severe accident research, accident progression analysis by system code is one aspect, but the mechanistic analysis of local phenomenon is also important to understand the severe accident scenario and to improve the models of system code.

Erosion of solid structure impinged by molten jet could be found in many places in the progression of nuclear severe accident, such as molten corium impinging onto the lower core plate and the reactor pressure vessel (RPV) wall and molten corium impinging on the pedestal of drywell when the RPV fails. Such attacking scenarios could lead to local hotspots in lower core plate, RPV wall and drywell, and then erosion and localized break occur. Considering the combination of molten jet temperature, solid structure temperature, melting point of molten jet and melting point of solid structure, the erosion behavior of solid structure could be classified into the following two modes as shown in Fig. 1 [1]. In Fig. 1(a) the molten jet freezing and solid plate melting occur simultaneously at the jet-plate interface, which is like the interaction of molten UO_2 jet with stainless steel (SS) structure; and in Fig. 1(b) the plate melting occurs at the interface without molten jet freezing, which is like the interaction of molten SS jet with SS structure. The crust and molten film formed at the jet-structure interface have significant effect on the erosion behavior and heat transfer.

Many studies have been reported on the erosion of solid structure impinged by molten jet. A laminar stagnation flow mode assuming a thin molten film at the jet impingement surface was developed by Swedish et al. [2], to describe the melting heat

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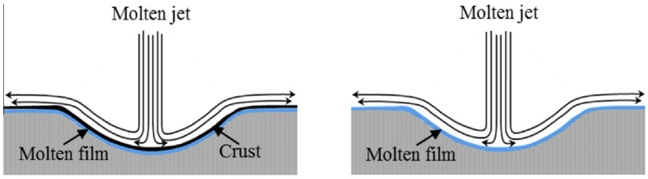

(a) (b)

Fig. 1. Configuration of a molten jet eroding solid plate.

transfer at the jet impingement region despite turbulence condition. The model was used to predict melting rate of solid surface of ice, octane, P-xylene and olive oil impinged by upward flowing hot water jet. The predicted erosion rates agreed well with the experimental data. Furutani et al. [3] investigated the effect of molten film on plate erosion during jet impingement. Experiments were carried out using hot water at 333 to 363 K as liquid jet impinging upon solid plates made of Wood's metal and paraffin. An analytical solution developed by assuming a thin liquid film at jet-plate interface well predicted the erosion rate of solid plates, but such thin liquid film mode was not applicable for the conditions with a deep melt pool and crust formation in the eroded cavity. Epstein et al. [4] developed a theoretical laminar-axisymmetric flow mode to describe melting heat transfer in the presence of jet freezing during impingement. To verify the theoretical prediction a supporting experiment was also performed with hot water impinging upward and melting the bottom of octane and mercury rods. The melting rates observed in the experiment matched well with the prediction by the simple axisymmetric melt flow mode. Saito et al. [5] extended Epstein's model to turbulence region with simultaneous melting and freezing behavior taking place at the impingement region. The model was fitted from and compared with the result of NaCl jet–Tin plate test.

Powers [6] performed high-temperature melt experiment composed of 207–222 kg molten 304SS at about 1978 K impinging onto 9.5–76.2 mm thick steel plates, which indicated that the steel plates were eroded aggressively by the impinging jets; however, further experiment with coating of 0.2–2 mm thick urania (U_4O_9) on the surface of steel plates delayed the penetration by the very high-temperature melts, such as iron and alumina at 2673 K. Albrecht et al. [7] experimentally studied the erosion rate in depth and erosion volume of concretes impinged by molten corium jet that was simulated by alumina-iron thermite melt. An et al. [8] performed jet impingement experiment to investigate ablation characteristics of special concrete that was developed as one of the candidate protecting materials for the EU-APR1400 ex-vessel core catcher. The molten corium was simulated by zirconium-dioxide melt. From the post-examination of the concrete specimen, it was found that the concrete entire surface was uniformly ablated, which implied that the jet inertial impingement was not so effective to erode the specimen.

From above research survey we could find that a series of jet impingement experiments have been performed with simulant materials to provide experimental data for model validation, and some theoretical analytical models were developed to describe the erosion rate in depth of the solid structure. However, the above theoretical analytical models were derived and fitted from the experimental data with many assumptions, which cannot reflect the exact configuration at the jet-structure interface, and such models have limitations when applied to the real nuclear severe accident conditions. Therefore, numerical simulation becomes a necessary approach to mechanistically study and reproduce nuclear severe accident phenomena. As for the erosion of solid structure by molten jet impingement, it is a multi-phase and multi-component flow accompanied with large deformation, fragmentation and coalescence of the interface and free surface. The conventional grid based numerical methods have difficulties to treat such complex phenomena. It is necessary to introduce a new numerical method without relying on the experimental correlations for plate erosion behavior and heat transfer analyses.

Moving particle semi-implicit (MPS) method is a novel particle method for analyzing incompressible flow with fully Lagrangian description. It has advantages in capturing fluid interface and free surface with large deformation and fragmentation, and the problems of grid distortion and numerical diffusion could be avoided. MPS method has been successfully applied in various research fields involving multi-phase flow [9–13]. In terms of mechanistic study of nuclear severe accident phenomena, it was also applied to fuel–coolant interaction (FCI) [14,15], steam explosion [16], molten corium stratification [17,18], molten corium concrete interaction (MCCI) [19] and core degradation of sodium-cooled fast reactor (SFR) [20].

In the present study, the large eddy simulation (LES) was coupled with MPS method, named MPS–LES, to analyze the erosion behavior and heat transfer characteristics of the molten jet impinging onto solid plate. The simulated erosion depth with time was compared with the experimental data. The detailed configurations of crust and molten film formed at the jet-plate interface were well reproduced. A parametric study of the effects of molten jet velocity, diameter and temperature on the erosion behavior and heat transfer was also performed.

2. Numerical modeling

2.1. Governing equations and sub-particle scale (SPS) turbulence model

Governing equations consist of continuity, momentum and energy conservation equations. These equations are spatially filtered to separate variable scale into grid scale and sub-grid scale (SGS) in the grid-based large eddy simulation and into particle scale and SPS in the particle-based large eddy simulation.

$$\phi = \bar{\phi} + \phi' \tag{1}$$

where $\bar{\phi}$ is the particle scale component of variable ϕ, and ϕ' is the SPS turbulence component of variable ϕ. The filtered governing equations in Lagrangian description are as follows.

$$\frac{D\bar{\rho}}{Dt} = 0 \tag{2}$$

$$\frac{D\bar{\mathbf{u}}}{Dt} = -\frac{1}{\rho}\nabla\bar{P} + \nu\nabla^2\bar{\mathbf{u}} + \mathbf{g} + \nabla\cdot\tau \tag{3}$$

$$\frac{D\bar{T}}{Dt} = \alpha\nabla^2\bar{T} + \nabla\cdot\mathbf{\Theta} \tag{4}$$

where ρ is density, $\mathbf{u}$ is velocity vector, t is time, P is pressure, ν is kinematic viscosity, $\mathbf{g}$ is gravity, T is temperature, α is thermal diffusivity, $\boldsymbol{\tau}$ is SPS turbulence stress, and $\mathbf{\Theta}$ is SPS turbulence heat flux. The SPS terms in the governing equations account for the energy transfer from large scales to small scales of turbulence. According to the Smagorinsky model, the SPS turbulence stress can be modeled as follows.

$$\tau_{\alpha\beta} = \bar{u}_\alpha\bar{u}_\beta - \overline{u_\alpha u_\beta} = 2\nu_t\bar{S}_{\alpha\beta} - \frac{2}{3}k_{\mathrm{SPS}}\delta_{\alpha\beta} \tag{5}$$

$$\nu_t = (C_s\Delta)^2(2\bar{S}_{\alpha\beta}\bar{S}_{\alpha\beta})^{1/2} \tag{6}$$

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