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Simulation of the QUEOS Experiment using the 2D and 3D Rigid Dynamic-Moving Particle Semi-Implicit Method

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1. Introduction

Particle dissipation and mixing in liquid are common multiphase phenomena not only in nature and but also in industrial processes. Also, It is one of important phenomena in nuclear safety analysis on severe accidents associated with the coolability of the corium debris bed, in which the characteristics of the porous corium debris bed such as local porosity distribution, debris bed configuration, debris size distribution, porous structure etc., determined by the corium jet break-up, precipitation, and mixing processes are considered to be of importance. Therefore, we developed a new computational tool, called ADDA (Analysis of Debris Dynamics and Agglomeration), based on an enhanced MPS (Moving Particle Semi-implicit) algorithm (Park, 2011) [1] to understand the complex debris dissipation and mixing phenomena and identify the roles of the debris characteristics in the process and verified against the QUEOS experiment (Meyer, 1996; 1997) [2, 3] performed at FzK in Germany.

2. Methods and Results

2.1. Computational algorithm

The description and formulations on the enhanced MPS can be found in Park's work [1]. In this section, the coupling way of these two methods is introduced.

The entire calculation is divided into two stages for each time step. The first stage is the MPS calculation in which external forces induced by gravity, surface tension, and viscosity are calculated into temporal velocities and the pressure Poisson matrix is solved iteratively. The particle motion information gained from the first stage including $\mathbf{u}_i^{**}$, $\mathbf{r}_i^{**}$, and P_i^{**} is transferred to the rigid body dynamics calculation of the second step. In the dynamics calculation, the velocity change generated by the MPS calculation is converted to the force by

$$\mathbf{F} = \frac{m_i(\mathbf{u}_i^{**} - \mathbf{u}_i^{n})}{dt}. \quad (1)$$

Using the above forces acting on each fluid particle's center of mass, the colliding contacts and the resting contacts are calculated to obtain the velocities of the next time step.

2.2. Description on the QUEOS experiment

In this paper, the verification of the ADDA code was performed against the QUEOS experiments which was designed to establish the data base for testing the heat and momentum transfer models in the FCI (Fuel-Coolant Interaction) multi-fluid codes. For the code verification, we selected the Q21 test among the QUEOS tests conducted in a non-boiling condition (ZrO_2 particles at the ambient temperature and water temperature of 99 °C.) since the prime objective of the present verification is the hydrodynamic interactions between solid and liquid particles in the processes of jet breakup, mixing and precipitation. In the Q21 tests, a total of 18000 ZrO_2 particles in a shape of a jet with a diameter of 100 mm and a corresponding mass of 7 kg and a volume of 1830 cm^3 was injected into a water pool for 55±5 ms, resulting the jet length of 27±3 cm. Each ZrO_2 particle has a diameter of 4.95 mm.

2.3. Particle precipitation and mixing simulation

To simulate the Q21 test of the QUEOS experiment, the initial configuration of the model is set as Figure 1. The width of the test section is 0.7 m and the water level is 1 m. The initial distance between particles, l_0, is set to be 0.013 m, the radius of interaction, r_e, is 2.1 l_0 and the kernel size for Laplacian is $4.0l_0$. The density of water is 1000 kg/m^3, viscosity of water is 0.00109 Pa·s, the surface tension coefficient of water is 0.0728 N/m, and the friction coefficient of ZrO_2 particle is set to 1.0. To make a two-dimensional equivalent geometry, the mass of a particle is set to 0.097 kg. The initial downward velocity of the particles is 5.05 m/s.

Fig. 2 shows the precipitation process of the experiment and the calculation. For the two dimensional calculation, the water level was overestimated comparing to the measured level. The calculated penetration velocity of the particles was lower than the measured data. However, the simulation re-created the jet breakup and penetration behavior observed in the experiment, and revealed the structural details of the jet breakup process, showing the jet surface and the leading edge instability and boundary stripping phenomena.

For the three dimensional calculation, the penetration velocity was lower than the measured and 2D data. However, the 3D calculation shows better results in simulating the shape of the bottom leftover as shown in

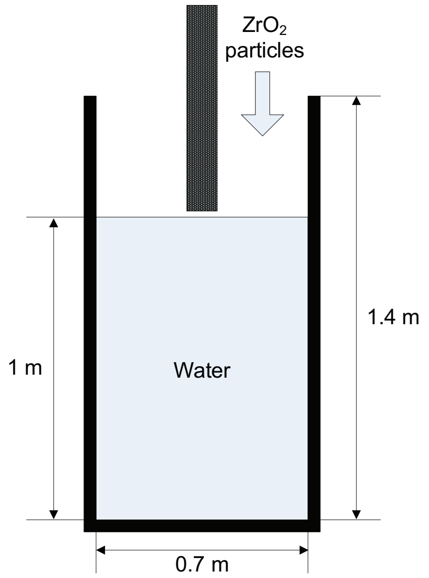

Figure 1: Schematic initial configuration of the Q21 test.

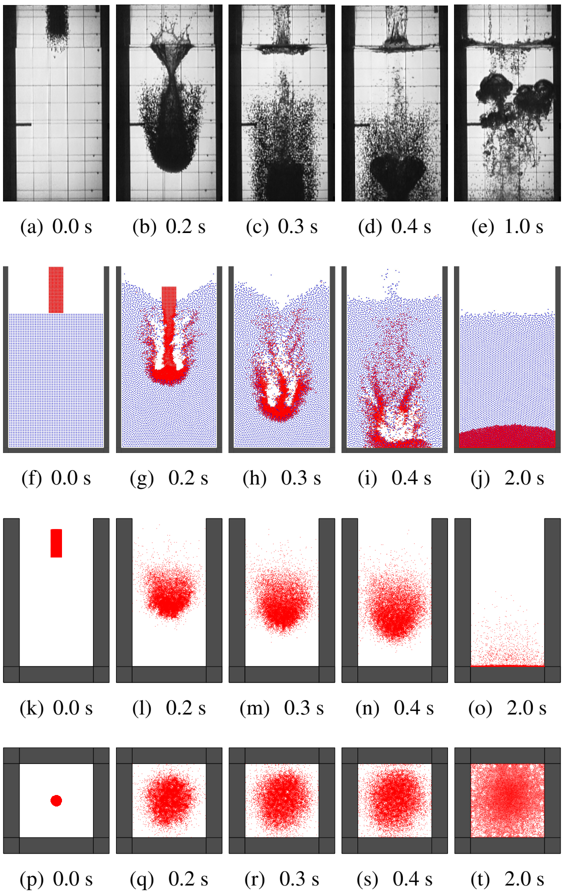

Figure 2: (a)-(e) show the results of Q21 test. (f)-(j) are the side views of the 2D calculation. (k)-(o) are also the side views of the 3D calculation. (p)-(t) are the calculation results from the top view.

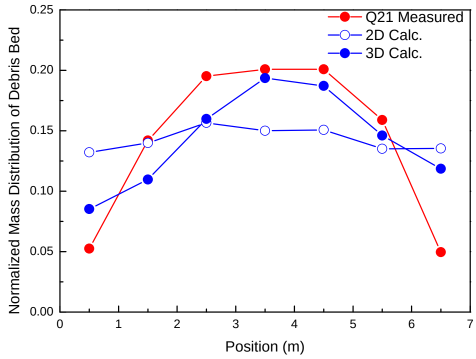

Figure 3: The normalized distribution of the particles on the bottom of the test vessel.

Fig. 3, in which the normalized mass distributions of spheres on the bottom of the test vessel are plotted.

3. Conclusions

In this paper, the ADDA code with the 2D and 3D RD-MPS algorithm[1] was used to simulate the non-boiling Q21 test of the QUEOS experiment. The code successfully created the complex particle jet mixing phenomena including particle penetration, mixing with surrounding coolant, dissipation and precipitation. Moreover, the code simulated the characteristic structure of particle jet breakup and mixing with surrounding liquid very well. Importantly, the enhanced stability of the code performance makes it possible to simulate the entire jet mixing process, predicting the particle bed formation on the bottom of the test vessel.

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