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3-D Simulation of Plunging Jet Penetration into a Denser Liquid Pool by the RD-MPS Method

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1. Introduction

We used the rigid body dynamics coupled moving particle semi-implicit (RD-MPS) method [1] to simulate a plunging liquid jet penetrating into a denser liquid pool in two and three dimensions. The simulating phenomenon is related to fuel-coolant interactions (FCI) during severe accidents in nuclear power plants when coolant water is forcedly injected into a melt pool. The simulation results suggested that the coupled model be useful in simulating dynamic interactions of multi-phase incompressible fluids as well as that the 3-D simulation for the plunging jet in a confined geometry predicted better agreement with experimental results than the 2-D simulation did.

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, and 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. Using the 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. Numerical analysis using the coupled method

Park et al. (1998) carried out experiments to investigate a plunging jet phenomenon with a water jet injection to a heavier pool liquid at non-boiling isothermal conditions of 20 °C [2]. In their experiment, a water jet with velocities of 3.8, 6, and 9 m/s, respectively was injected into a pool liquid of fluorinert with a density of 1.88. Their test section of 0.1 m-wide, 0.02 m-thick, and 0.2 m-deep was prepared to configure a two-dimensional visualization of the phenomenon. The diameter of the water jet was 10 mm smaller than 20 mm of the pool thickness. Photographs were taken by a video camera with a time interval of 1/30 seconds. This experiment was chosen for the model verification because of its multi-phase dynamics. In this calculation, only water jet and pool liquid particles are used and air particles are not considered. The water jet is initially positioned just above the melt surface and constantly injected to the pool. The initial distance between particles, l_0, is set to be 2.5 mm and the radius of interaction, re, is $2.1 l_0$. The water jet velocities (v_js) were 3.8, 6, and 9 m/s as in the experiment. The viscosities and the surface tensions of water and the pool liquid are 0.00109 kg/m-s and 0.0728 N/m, respectively.

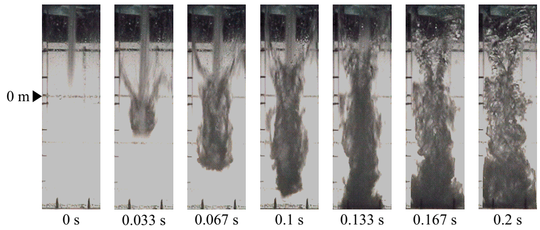
Figures 1 shows the results of the calculation for each initial velocity with the photos taken from the experiments. The water jet was initially injected with the specific velocity and pushed through the pool liquid forming a V-shaped pocket. The mechanical energy of the jet gradually lapsed down because of the buoyancy force created by small bubbles entrapped and carried into the pool liquid by the jet, and the repulsive force of the pool itself. The main driving mechanism, which determines the shape and behaviour of the jet interaction with the pool liquid, is the dynamic energy transfer caused by the physical collision of two different fluids.

Figure 2 shows plots of penetration depths for 3.8 m/s, 6 m/s, and 9 m/s of initial jet injection velocities. For the results of $v_j = 3.8$ m/s, the water jet was decelerated before touching the bottom of the pool liquid and began to ascend upward in the experiment. This was because the gas bubbles entrapped by the jet were beginning to rise up due to their buoyancy force. Even though there is no bubble model, the 3-D calculation is well following the penetration depth behaviour of the experiment. For the experimental results of $v_j = 6$ and 9 m/s, the dynamics energy of the jet was stronger than the buoyancy forces and decelerations were almost negligible. Namely, the calculated results were closer to the experimental results as the initial jet velocity increased.

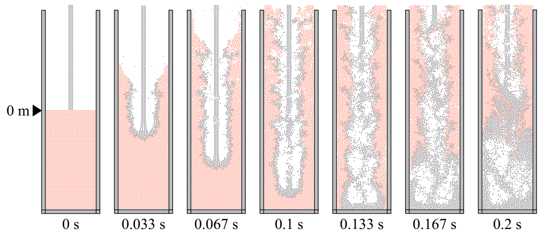
2.3. Consideration of jet penetration depth

As stated in the Ikeda's work [3], the penetration process consists of two stages (I and II) when a coolant jet is injected into a denser melt pool. At the stage (I), the jet seems to keep a constant velocity, which is in proportion to the inital velocity v_0. The jet penetration depth $L^{(I)}$ can be written as

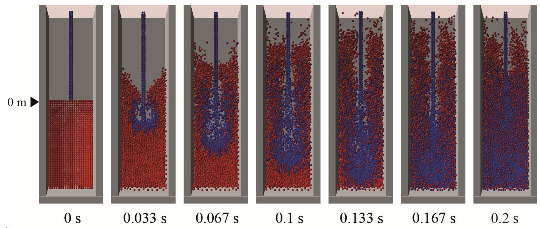
$$L^{(I)} = \alpha v_0 t, \tag{1}$$



(a) Experimental results

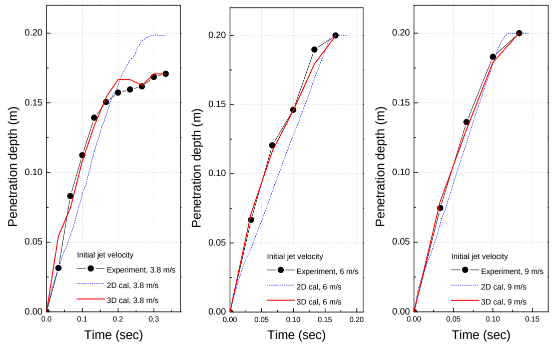


(b) 2-D calculation results



(c) 3-D calculation results

Figure 1: Results of water jet injection, v_j = 9 m/s.



(a) v_j = 3.8 m/s (b) v_j = 6 m/s (c) v_j = 9 m/s

Figure 2: The penetration depths compared with the measured data.

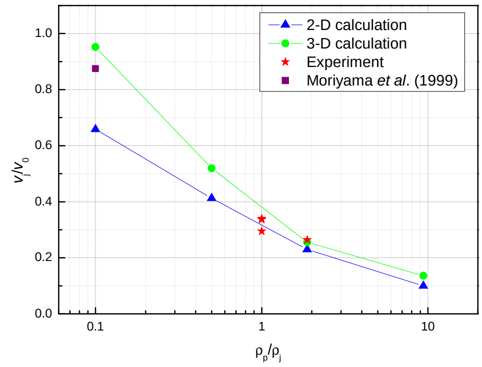


Figure 3: Correlation for α against the density ratio.

where α is a constant. To get information about α, we performed the jet penetration calculations with various density ratios between the pool liquid and injecting water jet (0.1, 0.5, 1.88 and 9.4, respectively) with the fixed velocity of 3.8 m/s. Fig. 3 shows the results for 2-D and 3-D calculations. We added Moriyama *et al.*'s data [4] for comparison. As shown in the figure, 3-D calculation is showing more reasonable prediction for the velocity ratio α.

3. Conclusions

In this study, the isothermal plunging water jets into a denser fluid pool were simulated to validate the coupled method of the MPS method and rigid body dynamics. In the plunging jet simulation, the mechanical energy transfer caused by the colliding of two different fluids was stably calculated and the penetration depth was well predicted because the coupled method calculated the mechanical energy transfer between fluids by directly applying rigid body dynamics. Moreover, the configurations of jet deformation were well predicted compared with the visual observation from the experiment. The simulation results suggested that the coupled model be useful in simulating dynamic interactions of multi-phase incompressible fluids as well as that the 3-D simulation for the plunging jet in a confined geometry predicted better agreement with experimental results than the 2-D simulation did.

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