Simulation of Energetic Isothermal Fuel-Coolant Interactions Using the Coupled Method of Rigid Body Dynamics and Moving Particle Semi-Implicit

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1. Introduction

In this study, the concept of the non-penetrating rigid body dynamics [1, 2, 3, 4] is coupled with the original the MPS method to increase the stability of the MPS calculations, especially for the multi-phase fluid condition. Note that the motions of systems of rigid bodies obey Newtonian dynamics, and a realistic simulation of rigid bodies demands that no body inter-penetrate with another.

To validate the algorithm of the MPS method coupled with rigid body dynamics, we chose the energetic isothermal FCI [5], which was simulated by Ikeda *et al.*, for the multi-phase condition.

2. Methods and Results

2.1. Computational algorithm

The basic descriptions and formulations on the MPS method and the simple rigid body dynamics are well described in the references, [6, 1, 2, 3, 4]. In this section, the coupling way of these two methods is introduced.

At the stage of initializing particle configurations, initial velocities, positions, and pressures are specified. A particle's diameter for the rigid body dynamics calculation is set to $0.9l_0$. If the diameter is set to the same as l_0, the fluid particles constantly conflict with each other and the contact point calculations become too complicated. If the diameter is much smaller than $0.9l_0$, the incompressibility is not well conserved and the overall calculation becomes identical to the result calculated only by the MPS method.

The entire calculation is divided into two steps for each time step. The first step 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 step, $\mathbf{u}_i^{**}$, $\mathbf{r}_i^{**}$, 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 as

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

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. These overall procedures are shown in Fig. 1.

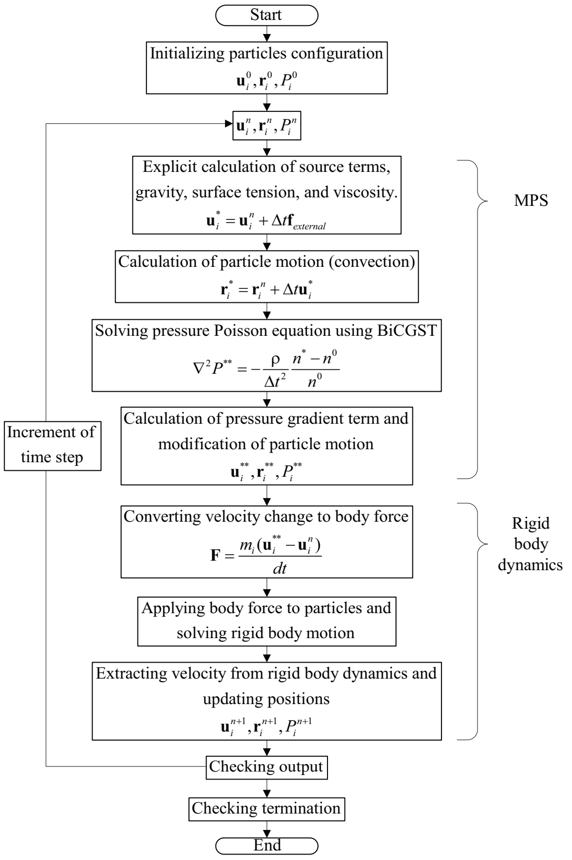
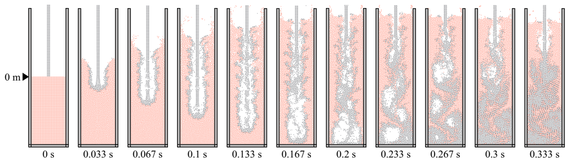


Figure 1: The overall algorithm of coupling the MPS method and rigid body dynamics.

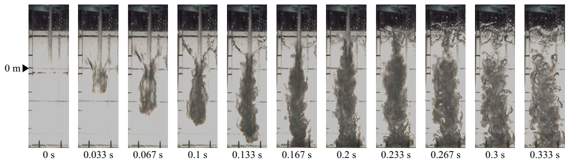
By the explicit combination of rigid body dynamics and the MPS method, the stability of fluid particle simulation can be considerably improved. Since each particle cannot get close to another particle due to the rigid body dynamics calculation, the compressibility of fluid can be firmly maintained. Also, the kinetic energy, before and after the contact of two particles, is preserved by the rigid body dynamics model.

2.2. Isothermal water jet injection into a melt pool

Park *et al.* [5] carried out experiments to investigate a plunging jet phenomena with a water jet injection to a heavier pool liquid at non-boiling isothermal conditions of 20 °C. In their experiment, a water jet with velocities of 3.8, 6, and 9 m/s, respectively was injected into



(a) Calculation results



(b) Experiment results

Figure 2: Results of water jet injection, v_j = 6 m/s

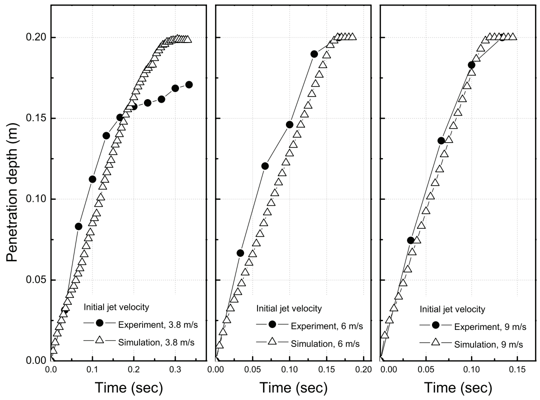


Figure 3: The penetration depth of the results comparing with the measured data

a pool liquid of fluorinert with a density of 1.88. Thier 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 2.5×10^{-3} m and the radius of interaction, r_e, is $2.1 l_0$. The viscosities and the surface tensions of water and the pool liquid are 1.09×10^{-3} (kg/m·s) and 7.28×10^{-2} N/m, respectively.

Figures 2 shows the result of the calculation (6 m/s) 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 behavior of the jet interaction with the pool liquid, is the dynamic energy transfer caused by the physical collision of two different fluids.

Figure 3 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. However, 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.

3. Conclusions

Rigid body dynamics was explicitly coupled with the MPS method. Through this coupling approach, the overall stability related to the incompressibility of a fluid was comparatively increased in the single-phase fluid simulation. As for the calculation of the multiphase fluids behavior, fluids interactions could be easily treated with highly improved stability preserving mechanical energy.

In this study, the isothermal plunging water jet into a denser fluid pool was 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 configuration 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.

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