Development of Fluid Interphase Particle for particle-based multiphase flow simulation

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I. INTRODUCTION

In particle-based multiphase flow simulations, the numerical stability and accuracy has been enhanced through the modification of modelling of density [1] and introduction of additional artificial forces [2], surface tension model [3], interpolation technique like overgrid methods [4] and so on. The problem is that most of them require smoothed interfaces in the compact support for stable differential operations, which implies a limitation of application to violent flow simulation with practical resolutions.

To enhance the applicability, this study targets a critical problem by the conventional ISPH for multiphase flows, which relates to the volume conservation based on the Pressure Poisson Equation using the particle number density. Further, in order to resolve the problem, a virtual particle, namely, Fluid Interphase Particle (FIP) is newly developed to consider the interparticle forces between different phases. The numerical stability and accuracy of the proposed FIP scheme is shown through benchmarks targeting oscillating droplet, rising bubbles, and gas-liquid dam break.

II. METHODS

In ISPH, the Pressure Poisson Equation (PPE) is based on the particle number density n as:

$$\frac{1}{n}\frac{D\rho}{Dt} = \frac{1}{n}\frac{Dn}{Dt}, \quad n_i = \sum_j V_j w_{ij}. \tag{1}$$

Then
$$\frac{D\rho}{Dt} + \rho\nabla\cdot\boldsymbol{u} = 0 \rightarrow \frac{1}{n}\frac{Dn}{Dt} + \nabla\cdot\boldsymbol{u} = 0. \tag{2}$$

For discretization, the locally averaged density of the target particle i is calculated using the neighboring particles j as:

$$\langle\rho_i\rangle = \sum_j m_j w_{ij} = \sum_j \rho_j V_j w_{ij}. \tag{3}$$

The problem is that particle mass m and density ρ vary in multiphase flow simulations. Therefore, the density ρ cannot be simply replaced by the particle number density n for multiphase flows as (1).

To solve the problem, a virtual interface particle called FIP (Fluid Interphase Particle) is newly introduced to consider the interparticle forces between different phases. As shown in Fig. 1, FIP is set at the same position with the same velocity, mass and density as the target real particle i. FIP connects not only to the target real particle i but also to FIP for the neighboring real particles k with different density. The fluid particles can consider the interphase connection only through their own FIP. FIP represents neighboring real particles k in the other phases. The kernel weight w of FIP is given to the target real particle i by the total weight of them as:

$$V_{i_F} w_{i\,i_F} = \underbrace{\sum_{k\in K} V_{k_F} w_{i_F k_F}}_{\text{The other phases } K}, \quad K = \{\rho_i \neq \rho_k \text{ and } k \neq FIP\}. \tag{4}$$

Where the subscript F denotes FIP of particles i and k. Since the position and volume of each FIP is the same as its target real particle, the kernel weight between FIP gets; $V_{k_F} w_{i_F k_F} = V_k w_{ik}$. Using this relation and (4), the locally averaged density is newly obtained as:

$$\langle\rho_i\rangle = \underbrace{\rho_{i_F} V_{i_F} w_{i\,i_F}}_{\text{FIP}} + \underbrace{\sum_{l\in L} \rho_l V_l w_{il}}_{\text{The same phase } L} = \rho_i \sum_{j\in J} V_j w_{ij} = \rho_i n_i\,;$$

$$L = \{\rho_i = \rho_l \text{ and } l \neq FIP\}, \quad J = K \cup L. \tag{5}$$

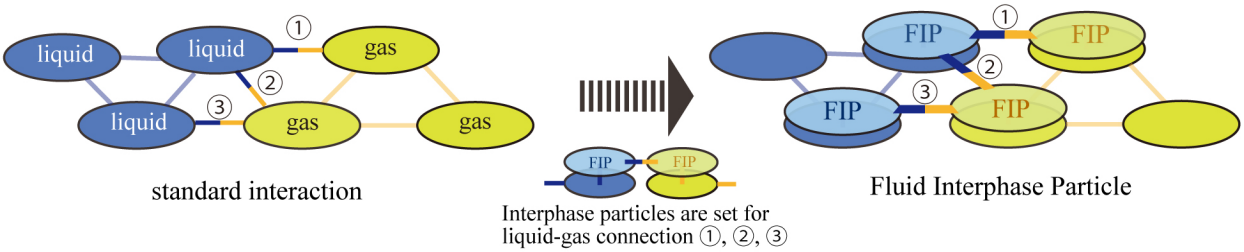

Figure 1. Graphical presentation of the proposed scheme: Fluid Interphase Particle

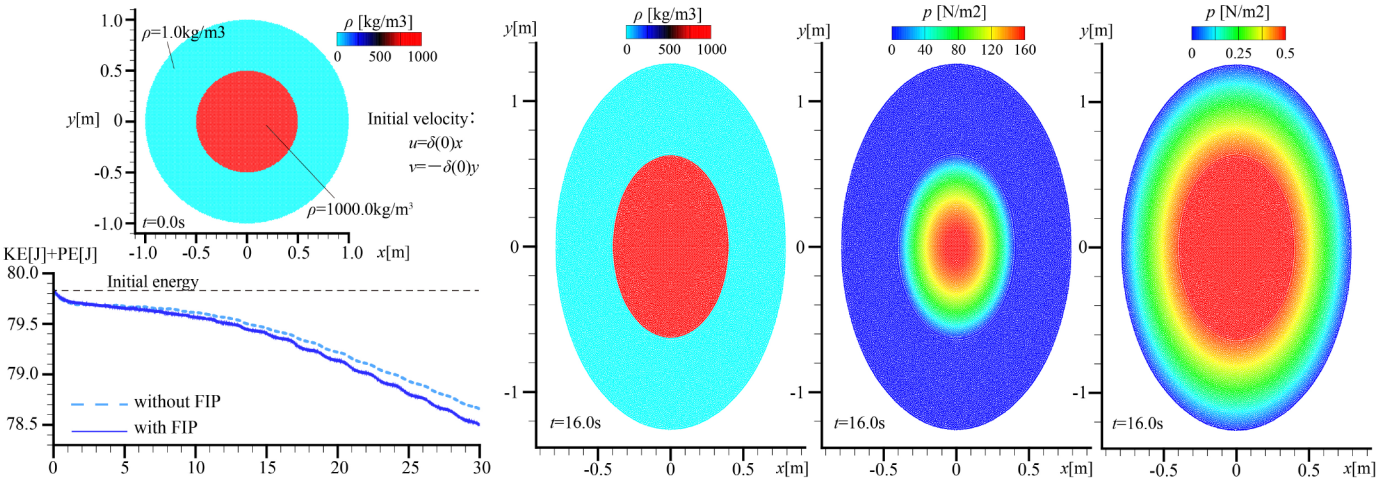

Figure 2. Simulation of Oscillating droplet under a central force field (Snapshots: the result by FIP)

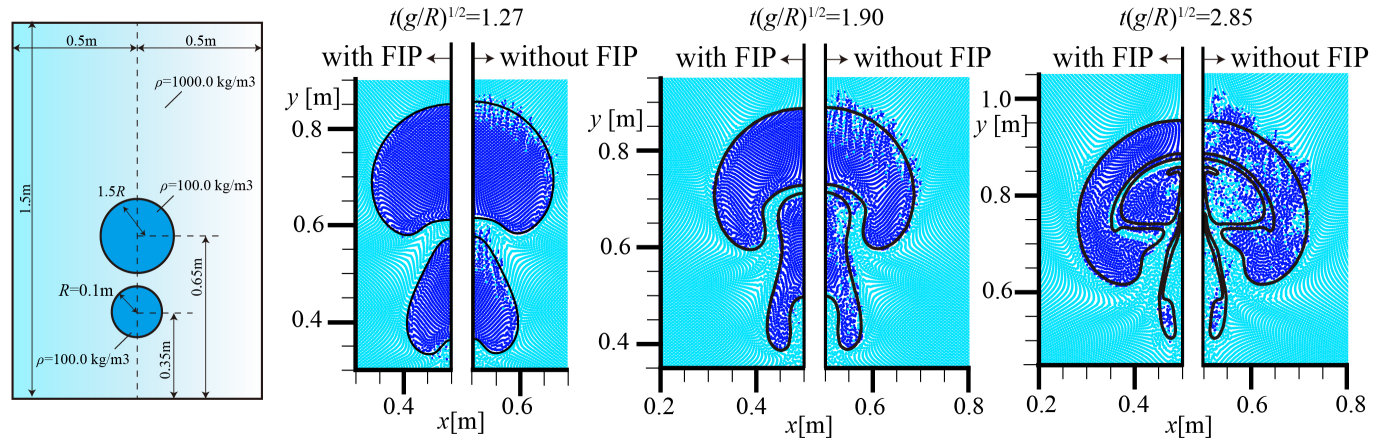

Figure 3. Simulation of merging of two rising bubbles (Black lines: the Level-set method [3], Blue particles: the present simulations)

The differential operators are given as:

$$\langle \nabla \boldsymbol{\phi}_i \rangle = \underbrace{\boldsymbol{\phi}_{i\,i_F} V_{i_F} \nabla w_{i\,i_F}}_{\text{FIP}} + \underbrace{\sum_{l \in L} \boldsymbol{\phi}_{il} V_l \nabla w_{il}}_{\text{The same phase } L}. \quad (6)$$

$$\langle \nabla^2 \boldsymbol{\phi}_i \rangle = \underbrace{\boldsymbol{\phi}_{i\,i_F} V_{i_F} \nabla^2 w_{i\,i_F}}_{\text{FIP}} + \underbrace{\sum_{l \in L} \boldsymbol{\phi}_{il} V_l \nabla^2 w_{il}}_{\text{The same phase } L}. \quad (7)$$

FIP behaves as a kind of agent of the target real particle for the interaction with the neighboring real particles in the other phases. The real particles between the different phases are connected through their own FIP in PPE. FIP is also built into PPE as an additional particle, and the pressures of all the particles including FIP are simultaneously solved in the same discretization space. Thanks to (5), the real particles are connected to only the particles which have the same density in (3). Therefore, the density can be replaced by the particle number density n as (1) for the real particles. FIP is redistributed at every time step, thus, the density errors given to FIP are reset without affecting the real particles.

III. Simulation Results and Discussion

To examine the performance of the proposed FIP scheme, simulations targeting oscillating droplet with two fluids under a central force field, merging of two rising bubbles, and gas-liquid dam break are implemented. Considering the practical applicability, the Courant number α_{dt} is set as α_{dt}=0.1 in all the simulations. As a basic set, CISPH-HS-HL-LBP-ADS [5] is applied to enhance the numerical accuracy and stability.

A. Oscillating droplet under a central force field

A widely simulated benchmark, 2D oscillating droplet comprising two fluids under a central force [6] is implemented to show the performance of FIP. An external force $\boldsymbol{f}_{ex}$ is given as $\boldsymbol{f}_{ex}=-\Omega^2\boldsymbol{r}$. The particle size d is set as d=0.01m. The initial condition and the numerical results with density and pressure distributions are shown in Fig. 2. The density ratio between the two fluids is 1:1000, and the surface tension is not considered. The time series of the summation of the potential and kinetic energy is also shown in the figure. FIP has 0.017% larger energy loss at t=30.0s. The way of interphase connection in PPE is quite

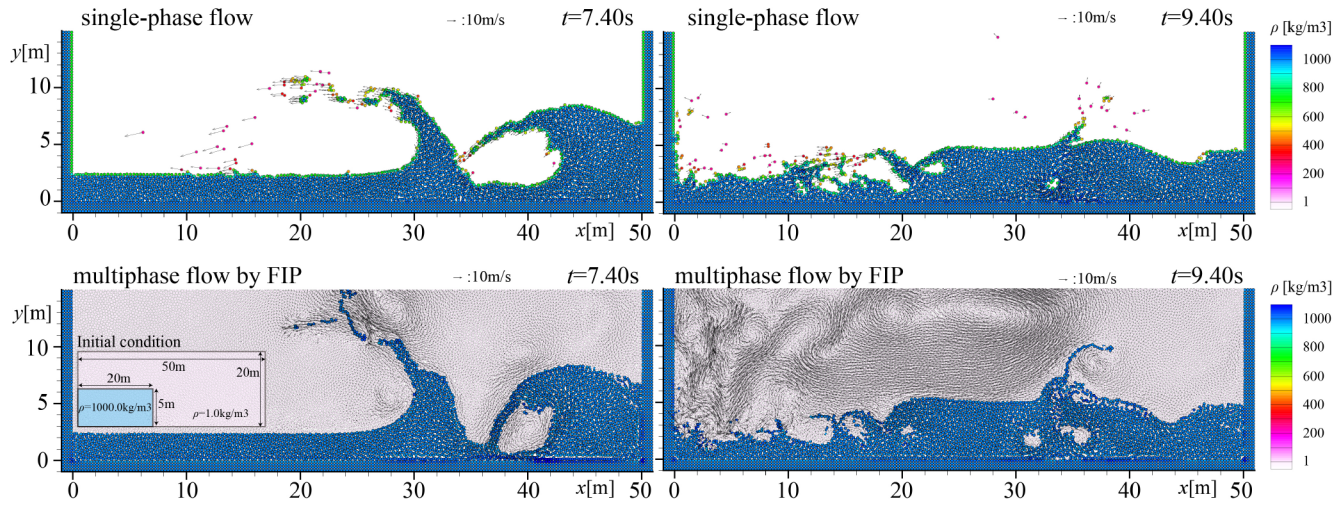

Figure 4. Simulation of dam break (top: single-phase flow, bottom: multiphase flow by FIP)

different between them. However, the performance is almost similar to each other. From the snapshots, the pressure field is highly smooth even around the interface despite their sudden change of pressure due to density difference.

B. Merging of two rising bubbles

Merging of two rising bubbles [3] is simulated by FIP. The initial condition is shown in Fig. 3. Two bubbles merge as they rise in the denser fluid. The surface tension is not considered here, thus the Bond number B_o is set as B_o=∞. The particle diameter d is set as d=0.005m. The density of the denser fluid ρ_d is ρ_d=1000.0kg/m^3 and the density of the lighter fluids ρ_l corresponding to the bubbles is ρ_l=100.0kg/m^3. The other parameters are consistent with [3]. Fig. 3 shows snapshots of particles with density fields and a result obtained using the level-set solver [3]. If FIP is not applied, the interfaces of the rising bubbles cannot be captured accurately, and some particles scatter significantly. While the interfaces are smoothly reproduced by FIP even though it does not contain an additional artificial force to capture the interfaces.

C. Dam break

2D simulations targeting a dam break are implemented to show the enhanced performance by FIP for violent multiphase flows. The density ratio of gas to liquid is 1:1000. For ease, the gas is treated as an incompressible flow and the surface tension is omitted. The particle size d is set as d=0.25m. The simulation of multiphase flow without FIP breaks up at an early stage. Here, results of a single-phase flow and a multiphase flow by FIP are shown in Fig. 4. FIP achieves a stable simulation even when it includes breaking waves with scattered gas and liquid particles. Compared with the single-phase flow simulation, the liquid surface particles are more continuously and tenaciously connected in the multiphase flow simulation, e.g. a tip of the splash at t=7.40s and another one around x=35m at t=9.40s. Around the interfaces between gas and liquid phases, they are not regarded as free surfaces in the multiphase flow simulation, and their vicinity particles are built into the PPE considering their volumes as parts of a continuum. Noteworthy is that this simulation is stably implemented with practical time steps based on the Courant number α_{dt}=0.1 without an apparent numerical diffusion around the interfaces.

IV. Conclusion

This study developed a new stable multiphase scheme for ISPH. Considering the consistency with the source term of PPE, a virtual particle FIP (Fluid Interphase Particle) is newly introduced to consider the interparticle forces between different phases as an agent of the target real particle. This model does not include any artificial stabilizing forces, and is not based on the overgrid techniques. The enhanced performance was shown by simulating benchmarks targeting oscillating droplet under a central force field, merging of two rising bubbles, and dam break. Its performance of energy conservation and reproducibility of interfaces between different phases, and its outstanding stability were shown through the simulations. For future work, a surface tension model and an additional framework to consider the compressibility of the gas phase are required for more physical reproduction of gas-liquid multiphase flows.

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