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An MPS-based particle method for simulation of multiphase flows characterized by high density ratios by incorporation of space potential particle concept

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HIGHLIGHTS

- A refined particle method is proposed for simulation of multiphase flows with high density ratios.
- A consistent coupling scheme is developed based on the concept of space potential particles.
- The coupling scheme guarantees the continuity of pressure and space at phase interface.
- The method preserves density discontinuity at the phase interface.
- The method is shown to have good accuracy and convergence property.

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ABSTRACT

Simulation of multiphase flows characterized by high density ratios is targeted by using a refined particle method. The proposed method is founded on Moving Particle Semi-implicit (MPS) method which is a projection-based particle method. The proposed method comprises of a decoupled two-step computational algorithm through application of a consistent scheme for coupling the light/heavy phases by incorporating the concept of Space Potential Particles (SPP). The proposed coupling scheme guarantees the continuity of pressure and space (volume conservation) at the phase interface without any need for commonly applied density smoothing/averaging schemes or application of numerical stabilizing terms. Verification of the proposed multiphase particle method is conducted through the simulations of four benchmark tests and the method is shown to possess acceptable accuracy and convergence properties.

1. Introduction

Multiphase flows are widely encountered in engineering and environmental applications. However, numerical simulation of multiphase flows, and in particular liquid–gas flows, is challenging mainly due to the sharp and abrupt density drop at the phase interface that would lead to a mathematical discontinuity of density and accordingly a discontinuous pressure gradient field.

A recent interest has been devoted to development of Lagrangian meshfree methods, namely, particle methods that possess inherent advantages in simulating convection-dominated flows with moving boundaries [1–4], as in case of multiphase fluid flows. In general, there are two well-known macroscopic particle methods, namely, SPH (Smoothed Particle

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Hydrodynamics) [5] and MPS (Moving Particle Semi-implicit) [6] methods. Many studies have been conducted to enhance the accuracy and reliability of both SPH (e.g. [7–11]) and MPS (e.g. [12,13]) methods.

In the context of particle methods, there have been several attempts to propose accurate multiphase methods that can deal with the mathematical discontinuity of density at the phase interfaces (e.g. [14–16]). These attempts are classified in the recent review paper by Gotoh and Khayyer [17]. In general, almost all particle-based methods for simulations of multiphase flows of high density ratio incorporate special numerical treatments at the phase interface. These treatments include application of numerical stabilizing terms (such as artificial repulsive pressure force [18] or artificial surface tension force [19]), particle shifting scheme [20,21], density averaging [22] or density smoothing schemes [23–26].

The most straightforward approach to tackle the challenge related to density discontinuity corresponds to application of a density smoothing scheme where a spatially averaged density is reconstructed based on density distribution at the interface zone. Despite their effectiveness, such smoothing schemes are likely to downgrade the method's reliability and accuracy, especially in presence of thin layers of entrapped air as in case of wave slamming [23]. Another possibility is to merely reformulate the scheme related to pressure gradient acceleration by incorporating a spatially averaged density [22]. Such reformulation will also have a smoothing effect on the overall reproduced physics. Indeed, application of numerical stabilizing terms as well as particle shifting schemes [27] are likely to result in unphysical reproductions and violation of energy/momentum conservation [21], especially in practical simulation of multiphase fluid flows. On the other hand, the domain separation method (e.g. [28]) can be considered as one of appropriate approaches for simulation of multiphase flows without special numerical treatments at the phase interface, although the method is validated only for low density ratio. Thus, it is important to develop a numerical method that can reliably tackle the mathematical discontinuity of density in a physically sound and conceptually consistent manner.

In this study, the recently proposed concept of Space Potential Particle (SPP) [12] is applied to develop a particle method for simulation of multiphase flows characterized by high density ratios. The SPP concept was proposed in the context of single-phase free-surface flows to represent a potential in void space for the fluid phase to reproduce physical motions of particles at and in the vicinity of free-surface through a particle–void interaction. In this study, the SPPs are incorporated as an interface boundary condition for the heavier phase to guarantee the pressure continuity as well as the space continuity at the phase interface. The continuity of space is a key issue to maintain regularity of particle distributions and thus to achieve accurate and consistent reproductions.

The paper is organized in the following manner. In the next section, the proposed multiphase MPS is thoroughly described. Section three is dedicated to verification tests by conducting several numerical benchmark tests, including a static multi-fluid subjected to an exponentially excited sinusoidal external acceleration, oscillating drop under a central force field [18], standing gravity wave [27] and sloshing flow [29]. Finally, in Section 4, the concluding remarks and insights on future works will be discussed.

2. Proposed multiphase MPS method

2.1. Governing equations

The proposed method is capable of dealing with both compressible and incompressible phases simultaneously. For the incompressible phase (water phase), which is also considered to be inviscid, the continuity and Euler equations are considered as follows:

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\boldsymbol{u} = 0 \tag{1}$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla p + \boldsymbol{g} \tag{2}$$

where D/Dt stands for Lagrangian time derivative, $\boldsymbol{u}$ represents particle velocity vector, t stands for time, ρ signifies fluid density, p symbolizes particle pressure and $\boldsymbol{g}$ denotes gravitational acceleration vector [$\boldsymbol{g} = (0, -9.8)\ \mathrm{m/s^2}$].

For a compressible fluid flow (air phase) and by consideration of the air compressibility, the continuity equation is expressed as follows:

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\boldsymbol{u} = \frac{1}{{C_s}^2}\frac{Dp}{Dt} + \rho\nabla\cdot\boldsymbol{u} = 0 \tag{3}$$

where C_s is the speed of sound in air.

The above governing equations are solved in the framework of a projection-based particle method, namely, the MPS (Moving Particle Semi-implicit) method [30–32]. In this study, a set of refined schemes, namely, Higher-order Source term of PPE (HS) [33], Higher-order Laplacian model (HL) [34], Compressible–Incompressible Error-Compensating Source term of PPE (CIECS) [23], Gradient Correction (GC) [35] and Dynamic Stabilization (DS) [36] are applied to enhance the stability and accuracy of simulations. As previously mentioned, the concept of Space Potential Particles (SPP) [12] is incorporated in the coupling scheme of air/water phases. A brief explanation of standard MPS method is presented in Section 2.2. The applied refined schemes as well as the SPP concept are briefly introduced in Sections 2.3 and 2.4, respectively. Section 2.5 is dedicated to the algorithm and coupling scheme of the proposed multiphase MPS-based method.

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