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An efficient level set remedy approach for simulations of two-phase flow based on sigmoid function

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HIGHLIGHTS

- A sigmoid function is used to describe the relationship between signed distance function and liquid volume fraction.
- An improved criterion on determining the mass correction is introduced to predict a more accurate interface location.
- Relative CPU cost of the remedy procedure is greatly reduced from 100%to less than 10% by using the sigmoid function.
- A more accurate interface location is obtained while the excellent mass conservation of the previous method is inherited.

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ABSTRACT

The current work presents an improved, concise and inexpensive remedy approach for level set methods to deal with the mass non-conservation issue especially in large-scale simulations, where computational cost is always a constraint limiting broad applications. In this work, a sigmoid function originated from the work of Olsson and Kreiss (2005) is further utilized to describe the local relationship between the signed distance function of level set method and the liquid volume fraction. An improved criterion on determining the correction within relevant cells is introduced. And the upwind scheme for curvature calculation is implemented to handle small and/or thin structures. Several benchmark validations and gas-liquid flow problems are carried out to assess the approach. The main advantage of this approach is that the additional CPU cost for multiphase solver caused by remedy procedure, when relative to that without remedy, can be greatly reduced from about 100% to less than 10%, making it suitable for large-scale simulations. This approach also gains a higher accuracy in predicting the interface location while inherits the good performance of the previous method on ensuring mass conservation. Analyses prove that the level set remedy approach is suitable and reliable in simulating two-phase flows.

1. Introduction

Two-phase flow with complex interface topologies is a ubiquitous phenomenon existing in a wide range of technical applications. During an atomization process, for instance, the topology of the liquid changes drastically from a jet or a wavy jet to sheets, ligaments, and other not well defined liquid parcels. Eventually, the liquid becomes a set of droplets. It is crucial to explore the intrinsic mechanisms and accurately predict the interface topology change in two-phase flows.

Recently, high-resolution numerical methods, e.g. direct numerical simulation (DNS), combined with massively parallel supercomputers make it possible to obtain a satisfactory representation of gas-liquid flows (Ménard et al., 2007; Fuster et al., 2009; Shinjo and Umemura, 2010). Demoulin et al. (2013) commented that a new level of understanding has been achieved thanks to DNS applications in exploring dense flow regions and in developing new models, yet unresolved areas remain. Several great challenges prove to be the hindrances (Gorokhovski and Herrmann, 2008) in simulating gas-liquid flows:

(1) Frequent evolution of phase interface topology;
(2) Jump conditions across the interface;
(3) Singularity of surface tension active only at the interface.

The above three challenges involve a common problem of interface localization and transport. So an appropriate method is required. Prerequisites for such method include high accuracy, robustness, flexibility and the capability to simply extract the interface normal and curvature. Moreover, in most cases the two phases can be considered as two separate and immiscible species,

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which means that the method should also ensure the mass of each phase being exactly conservative.

There are two main families of methods to locate and transport the interface, i.e. the interface tracking method and the interface capturing method. The former includes the front tracking method (Unverdi and Tryggvason, 1992; Glimm et al., 1998), the cut cell method (Chang et al., 2013), the arbitrary Lagrangian-Euler method (Braess and Wriggers, 2000) and so on. It typically either uses a moving mesh that deforms with the interface or advects a set of massless particles in a Lagrangian way. When the particles represent fluids rather than interfaces, a post process is needed to detect the free interface, for example in the smoothed particle hydrodynamics method (Marrone et al., 2010). Although these methods allow a nice resolution of property jumps, they are expensive and somehow complex to realize as they cannot handle the topology automatically. The latter uses a fixed Eulerian scalar field to implicitly represent the interface. Two classes of this methodology are widely used: the level set (LS) method (Osher and Sethian, 1988) and the volume of fluid (VOF) method (Hirt and Nichols, 1981). It's noteworthy that the phase field method (Yue et al., 2004) is also a popular interface capturing method especially good for problems with free energy. This method is similar to the LS method to some extent, but suffers from more constraints (Chiu and Lin, 2011). As a result, the present paper focuses on the VOF and LS methods.

Since its transport equation contains volume information, the VOF method has an excellent mass conservation property. But this method is restricted in applications due to the complex reconstruction of the interface as well as the difficulty in evaluating the interface normal and curvature. In contrast, the LS method, implicitly representing the interface as the zero level set of a continuous function, is straightforward to calculate the interface normal and curvature. Its parallelization is also convenient.

Nevertheless, the LS method is typically plagued by mass non-conservation issues, i.e. unphysical loss or gain of one phase, as time evolves. Luo et al. (2015) indicated that the discretization of LS equation is one of the main reasons, which usually leads to significant numerical dissipation in areas of high curvature or other under-resolved regions (Losasso et al., 2006). So it is a straightforward attempt to refine the mesh locally to decrease the numerical errors and therefore increase the accuracy of interface location. This refinement can either be used only for interface location methods, e.g. the refined level set grid method (Herrmann, 2008) and the spectrally refined interface (SRI) approach (Desjardins and Pitsch, 2009), or be used for the Navier–Stokes equations too, e.g. the octree based method (Fuster et al., 2009) and the adaptive mesh refinement method (Zuzio and Estivalezes, 2011). However, these attempts are challenging to implement on parallelization and sometimes are extremely complicated. To retain the simplicity of the original LS method, a strategy marked as accurate conservative level set (ACLS) method was firstly proposed by Olsson and Kreiss (2005) and then improved by many researchers (Olsson et al., 2007; Desjardins et al., 2008; Zhao et al., 2014). The idea is to use a hyperbolic tangent function instead of the signed distance function. This method has a good mass conservation. But it can lead to so-called flotsam and jetsam non-physically breaking off from the interface in under-resolved regions. Some researchers also tried to couple the LS method with another method to keep it conservative, for example the coupled level set/volume-of-fluid method of Sussman and Puckett (2000) and the particle level set method of Enright et al. (2002). While these methods and their variants (Hieber and Koumoutsakos, 2005; Sun and Tao, 2010; Wang et al., 2012) have better results, their cost becomes typically greater. Additionally, the implementation is complex.

In brief, different strategies to solve the non-conservation problem have already been accessible, but a more definitive solution is still on its way. When we take the requirements of engineering applications which are usually massive and complex in computation, into account, an easy-to-implement and CPU-cheap remedy approach is desired. Recently in our previous work, Luo et al. (2015) introduced the idea of Van der Pijl et al. (2005, 2008), in which no VOF reconstruction is needed, to a remedy procedure based on the local curvature of the interface. This method is flexible and useful to ensure the mass conservation. However, its cost can be huge when dealing with large-scale simulations, and its core distribution criterion on remedy proportion is fragmentary and still under development. Hence the present work aims to (1) greatly reduce the CPU cost using a so-called sigmoid function, (2) predict a more accurate interface location by develop a comprehensive distribution criterion while retain the excellent performance in mass conservation, and (3) make the remedy approach suitable and reliable for large-scale simulations.

The rest of this paper is organized as follows. Section 2 will present the governing equations. In Section 3, the sigmoid function and the improved level set remedy approach will be fully described. Then in Section 4 and Section 5, three benchmark validations of the proposed remedy approach and its further applications to complex flows are carried out. Results are detailedly analyzed. Discussions on CPU cost are placed in the latter section. Finally, some conclusions are drawn in Section 6.

2. Numerical methodology

2.1. Incompressible Navier-Stokes equations

To describe the immiscible gas–liquid flows, the incompressible Navier–Stokes equations are introduced. The continuity and momentum equations can separately be written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot (\mu[\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T]) + \boldsymbol{g}, \tag{2}$$

where ρ is the density, $\boldsymbol{u}$ is the velocity vector, p is the pressure, μ is the dynamic viscosity and $\boldsymbol{g}$ is the gravity acceleration.

The present paper assumed that the physical properties in each phases are constant, i.e. $\rho = \rho_l$, $\mu = \mu_l$ in the liquid phase and $\rho = \rho_g$, $\mu = \mu_g$ in the gas phase, but jump at the gas–liquid interface Γ, which can be represented as $[\rho]_\Gamma = \rho_l - \rho_g$, $[\mu]_\Gamma = \mu_l - \mu_g$. The velocity crossing the interface remains same, i.e. $[\boldsymbol{u}]_\Gamma = 0$, while the pressure at the interface is discontinuous and expressed as

$$[p]_\Gamma = \sigma\kappa + 2[\mu]_\Gamma \boldsymbol{n}^T \cdot \nabla \boldsymbol{u} \cdot \boldsymbol{n}, \tag{3}$$

where σ is the surface tension coefficient, κ is the curvature and $\boldsymbol{n}$ is the unit normal vector of the interface.

2.2. Level set equations

The classical LS method (Osher and Sethian, 1988) implicitly represents the interface as the zero level set of a continuous function, which is usually defined as the signed distance function:

$$|\phi(\boldsymbol{x}, t)| = \min |\boldsymbol{x} - \boldsymbol{x}_\Gamma|, \tag{4}$$

where t is time and $\boldsymbol{x}_\Gamma$ corresponds to the closest point on the interface from $\boldsymbol{x}$. The function regards $\phi(\boldsymbol{x}, t) > 0$ as liquid phase, $\phi(\boldsymbol{x}, t) < 0$ as gas phase and $\phi(\boldsymbol{x}, t) = 0$ as the interface. Because