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REVIEW ARTICLE

Ghost-Fluid-Based Sharp Interface Methods for Multi-Material Dynamics: A Review

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Abstract. The ghost fluid method (GFM) provides a simple way to simulate the interaction of immiscible materials. Especially, the modified GFM (MGFM) and its variants, based on the solutions of multi-material Riemann problems, are capable of faithfully taking into account the effects of nonlinear wave interaction and material property near the interface. Reasonable treatments for ghost fluid states or interface conditions have been shown to be crucial when applied to various interfacial phenomena involving large discontinuity and strong nonlinearity. These methods, therefore, have great potential in engineering applications. In this paper, we review the development of such methods. The methodologies of representative GFM-based algorithms for definition of interface conditions are illustrated and compared to each other. The research progresses in design principle and accuracy analysis are briefly described. Some steps and techniques for multi-dimensional extension are also summarized. In addition, we present some progresses in more challenging scientific problems, including a variety of fluid/solid-fluid/solid interactions with complex physical properties. Of course the challenges faced by researchers in this field are also discussed.

AMS subject classifications: 35L45, 65C20, 65M06, 65N85, 74F10

Key words: Multi-material flows, sharp-interface method, ghost fluid method, modified ghost fluid method, fluid-solid interaction, multi-material Riemann problem.

1 Introduction

The multi-material interface dynamics is of interest in many fields of engineering and science. For instance, a detailed understanding of gas-liquid flows in supersonic combustion contributes to the development and effective operation of supersonic ramjet engine

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and other combustion systems involving fuel drops in high-speed airflow. The evolution of an underwater explosion under a free surface is another scientific field related to multi-material flows, where the shock wave may impart severe loading on a submerged structure that could potentially damage the structure. The so-called interface here refers to all kind of interfacial phenomena with arbitrary topology shared by two or more immiscible materials, or the free surface. The interface dynamics here focuses on interactions between different fluids. More generally, it also includes the interaction between fluid and solid, as well as the interaction between solids.

Numerical simulation can be a more effective tool to understand multi-material flow fields and mechanical properties than experiments, and a lot of efforts to construct practical methods for various multi-material flows are put into by many researchers. A very challenging task is to properly define the material interface conditions. Unlike general transmissive or reflective boundary conditions which can be defined by directly using some known field variables, the corresponding interface conditions here are numerical attempts to produce boundary states that take into account the effects of wave interaction and material property. In general, currently popular high-order and high-resolution schemes, such as (weighted) essentially non-oscillatory ((W)ENO) schemes [1] and discontinuous Galerkin (DG) schemes [2], can work very successfully for single-material flows. However, when such schemes are employed directly to simulate multi-material flows, numerical inaccuracies usually occur in the vicinity of the material interfaces [3]. Various techniques have been developed to try to overcome the difficulties.

Some methods, usually called diffuse-interface methods or interface-capturing methods, relax the sharp character of material interfaces and thus regularize them over a small but finite region in analogy to shock capturing (Fig. 1(a)). In the γ-based model proposed by Abgrall [4], an additional transport equation in non-conservative form was solved for gases to prevent unphysical oscillations. The approach was then extended by Shyue to various equations of state (EOS) [5–7] and further developed to simulate problems where shock waves and interfaces interact [8,9]. Many recent developments in interface capturing also originate from the non-equilibrium seven-equation models proposed by Baer and Nunziato [10] and Saurel and Abgrall [11], or their simplified variants, the five-equation models [12,13]. The treatment of interfaces as diffuse zones may lead to unphysical mixtures of fluids during computations. Various sharpening techniques, therefore, are designed to prevent interfaces from being overly smeared or producing numerical instabilities, such as the tangent of hyperbola interface capturing (THINC) technique [14–16], the anti-diffusivity technique [17,18] and the artificial compression technique [19–21]. For incompressible flows, the phase-field method [22,23] adopts the Cahn-Hilliard equations to model mixture cells and usually requires a fine mesh resolution to resolve the interface. Recent developments of the diffuse-interface treatments can be found in the review paper by Maltsev et al. [24].

There are also a variety of sharp-interface methods or interface-tracking methods for multi-material flows. The sharp treatment of material interfaces enables two materials sharing an interface to have totally different EOS (Fig. 1(b)). The front-tracking (FT)