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An adaptive interface sharpening methodology for compressible multiphase flows

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ABSTRACT

A numerical methodology is developed to combine the advantages of adaptive mesh refinement (AMR) and interface sharpening technique. A five-equation compressible multiphase model with capillary and viscous effects is considered. The solver employs a wave propagation method along with the Tangent of Hyperbola for INterface Capturing (THINC) scheme. To calculate interface normal and curvature, an implicit filtering method is introduced which transforms the sharpened volume fraction variable to a variant with smoothed distribution. The accuracy and performance of our method is assessed through its application to multiple compressible interface problems ranging from high-Mach number shock–interface interaction to gravity driven flows with viscosity and surface tension effects. The results obtained for one-dimensional shock-tube and tin–air interaction problems are shown to compare well with analytical data. The flow patterns predicted for shock–bubble interaction and under-water explosion match those from the landmark experimental and numerical studies. Furthermore, the trends and values predicted for spike position in the Rayleigh–Taylor instability and bubble's center location in bubble rising are consistent with those found in literature. Particularly, it is shown that the coupled AMR-THINC method remarkably prevents excessive interface smearing and captures delicate interfacial features such as shear-induced instabilities encountered in shock–bubble interaction.

1. Introduction

Resolution of moving interfaces in compressible multiphase flows has been a subject of extensive numerical studies, due to its scientific and engineering applications [1–4]. In recent decades, many computational methods with different degrees of robustness and viability have been introduced for numerical simulation of compressible interface dynamics. Two different approaches exist to describe the interface motion based on the computational mesh considered as fixed or moving. Lagrangian approach treats the interface as an internal boundary followed by the computational grid [5,6]. In Eulerian approach, on the other hand, the computational grid is essentially stationary over the entire domain [7]. This eliminates the requirement of computational resources for regular regridding of the whole domain. There are two distinct methodologies in Eulerian framework to manage interfacial evolution, namely front-tracking and front-capturing.

In front-tracking methods the interface is represented by connecting a set of marker particles moving over the computational mesh. The underlying mesh may be totally fixed [8] or adapted in order for a grid line to superpose the

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interface [9,10]. Front-capturing methodology, on the contrary, considers the interface embedded into the computational mesh as an isosurface of a phase indicator variable [11]. Some of the most well-known front-capturing methods include level-set [12], volume of fluid [13], and hybrid algorithms of these methods [14,15]. All of the aforementioned Lagrangian and Eulerian methods are categorized as sharp interface methods (SIM). In sharp interface resolution of compressible multiphase flows, the main challenge is redefining the thermodynamic state of each fluid at phase boundaries. Different versions of ghost fluid methods have tried to address this issue [16–21].

The other, low cost yet sufficiently accurate, approach to handle the interface in compressible multiphase flows is the diffuse interface method (DIM), in which the interface is allowed to diffuse over a few computational cells. A mixing zone is thus formed across the interface and the thermodynamic properties of the flow are defined based on the combination of these properties for each phase [22]. Baer and Nunziato [23] are counted among the pioneers who derived a set of governing equations named "seven-equation model" for compressible multimaterial flows in diffuse interface framework. In another effort, Saurel and Abgrall [24] presented a more applicable seven-equation model to compressible multiphase flows.

Appropriate closures and the numerical procedures to solve these equations were further developed by researchers [25–27]. The inherent complications of this model caused the development of reduced models [28,29] where the two phases are presumed to be at mechanical equilibrium. Allaire et al. [28] proposed a five-equation model in which a single supplementary transport equation closes the system of equations. In their model, a separate mass conservation equation is solved for each phase while the momentum and energy equations are solved for the mixture. Murrone and Guillard [30] derived a five-equation model as a reduced version of the seven-equation model in the limit of zero relaxation time. Their model was further extended by [31] to include viscous and capillary effects. Later, Saurel et al. [32] presented a projection method to determine the average cell pressure using a relaxation system instead of calculating it directly from the equation of state.

Kreeft and Koren [33] proposed a new five-equation model in which the transport equation for the phase indicator variable was replaced by an energy exchange equation. Zhenget al. [34] presented an unstructured adaptive mesh solver for simulation of compressible multifluid flows in two-dimensions. Recently, Ansari and Daramizadeh [35] have developed a cost efficient high-resolution solver to investigate compressible multiphase and cavitation flow problems.

The objective of this study is to develop diffuse interface solver to simulate a diverse range of compressible multiphase flows. A variety of interface sharpening schemes could be used to remedy the inherent weakness of the DIM to capture the sharp gas–liquid interface [36–40]. In our development, THINC scheme [41–45] is adopted to suit our purpose of enhancing interface capturing because of its efficiency and applicability to the five-equation model.

The enhanced distribution of volume fraction, although representing the interface more accurately, does not supply the required compact support for approximation of interface derivatives. This is because variations of the enhanced volume fraction are embedded in a thin transition layer, its thickness comparable to the grid cell size. In our study, an implicit filtering procedure is proposed and employed to provide an auxiliary distribution of volume fraction with smoother variation to compute the interfacial gradients.

Additionally, our computational code exploits the adaptive mesh refinement technique (AMR) [46,47] in zones near the interface or containing high density gradients. The performance of our parallel flow solver is evaluated through numerical simulations of multiple compressible multiphase benchmark problems. The computational methodology is validated by comparing the results with numerical and experimental observations.

2. Governing equations and numerical scheme

The five-equation model including viscous terms, gravity and surface tension in Cartesian coordinate system is written as

$$\frac{\partial U}{\partial t} + \frac{\partial (F - F_v)}{\partial x} + \frac{\partial (G - G_v)}{\partial y} = S, \tag{1}$$

where

$$U = \begin{bmatrix} (\rho\phi)_1 \\ (\rho\phi)_2 \\ \rho u \\ \rho v \\ \rho E \end{bmatrix}, \quad F = \begin{bmatrix} (\rho\phi)_1 u \\ (\rho\phi)_2 u \\ \rho u^2 + P \\ \rho u v \\ u(\rho E + P) \end{bmatrix}, \quad G = \begin{bmatrix} (\rho\phi)_1 v \\ (\rho\phi)_2 v \\ \rho u v \\ \rho v^2 + P \\ v(\rho E + P) \end{bmatrix}, \tag{2}$$

$$F_v = \begin{bmatrix} 0 \\ 0 \\ \tau_{xx} \\ \tau_{xy} \\ u\tau_{xx} + v\tau_{xy} \end{bmatrix}, \quad G_v = \begin{bmatrix} 0 \\ 0 \\ \tau_{xy} \\ \tau_{yy} \\ u\tau_{xy} + v\tau_{yy} \end{bmatrix},$$

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