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A Gas-Kinetic Riemann Solver for Stiffened Gas Interface and its Application in Multimaterial Flows

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Abstract. A new kinetic model is proposed to solve the Riemann problem for stiffened gas interface from piecewise linear discontinuous initial distributions. In the model gas particles on each side of the fluid interface are reflected back from the interface, respectively, which is moving with a velocity to achieve the force balance between both sides. Compared with the existing Riemann solver, the present model can keep second order accuracy in both space and time. It is also capable of eliminating the numerical mixing at the fluid interface which is different to existing kinetic models. The new model is applied into the numerical flux calculation at a cell interface and with the help of homogeneous equilibrium mixture assumption within a cell, a new gas-kinetic scheme is developed for multimaterial flow with stiffened equation of state. The scheme is tested with several typical high-speed multifluid flows, including the water-gas shock tube flows and the shock-water cylinder interaction. The computed results are in good agreement with other numerical and experimental studies. Fluid interfaces as well as shock waves are sharply captured, free of numerical oscillation near the interface, even for density ratio up to about one thousand, which validate its high accuracy, strong robustness and good parallel performance.

AMS subject classifications: 82B40, 76T10, 76M25

Key words: Non-mixing interface model, stiffened equation of state, gas kinetic scheme, homogeneous equilibrium mixture model, stratified model.

1 Introduction

Compressible multimaterial flow is very important for many engineering applications, thus attracts a lot of numerical researches. Most of these existing studies are directly

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based on the macroscopic governing equations, such as the Euler equations, and the Riemann problem from a piecewise linear discontinuous initial distribution is usually solved to capture the field discontinuities [1–3]. The discontinuous initial data come from the limited physical model or numerical cell resolution to represent physical flow structure. For high speed multimaterial flow, besides the shock wave, the contact discontinuity is of more importance and thus special Riemann solvers with enhanced capability to capture fluid interface are developed, including the exact Riemann solver such as Godunov method [3–8], or approximate Riemann solver such as HLL/HLLC [2, 9–11]. Based on these Riemann solver, large amount of numerical schemes have been constructed with the combination of different numerical model to form the local Riemann problems, such as discrete equation method [12] or stratified model [5, 13, 14] for fluid mixture, or methods to clearly describe fluid interface, including front tracking [15, 16], front capturing such as VOF [17, 18] and level-set [19, 20], and the ghost fluid method [21, 22]. However, it is still a big challenge for a CFD method to capture the instability of fluid interface and the mixing of different fluids with the requirement of accuracy, resolution, conservation and robustness, especially for high Mach number and large density ratio [23, 24].

Based on the mesoscopic gas-kinetic theory, the gas-kinetic scheme (GKS) has been developed and shown good balance between high accuracy and strong robustness in various flow fields, especially in high speed flows [25]. To simulate multifluid flows, one strategy is to introduce a passive scalar to represent the mass fraction of different gas [26–28]. Another is to compute the evolution of different fluid separately, with suitable model accounting for their interactions, such as those with two mass species [29–31]. Through this way, a gas-kinetic scheme for two-phase flow has also been developed to recover the Baer-Nunziato model [32, 33]. Based on the equilibrium mixture model of different gases with stiffened equation of state (EOS), a GKS for gas-water flow has been constructed and shown good performance in many typical tests [34]. However, due to the numerical mixing not only inside a grid cell, but also at a cell interface, the fluid interface is smeared out to some extent which is also observed in other studies. Here the numerical mixing comes from the finite grid cell size which is much larger than the width of physical interface in most cases and sometimes may result in pressure oscillation near the material interface or contact discontinuity, especially when using local thermodynamic equilibrium assumption [10]. To eliminate the oscillation in inviscid flow, the kinetic flux vector splitting (KFVS) was modified and extended to stiffened gas flow [35–37]. The KFVS was also applied for solving a reduced five-equation and six-equation two-phase model [38, 39]. As the numerical dissipation of KFVS is in proportion to the time step, the numerical mixing is still evident and also may encounter difficulty in viscous flow. Thus a kinetic non-mixing solver for Riemann problem is necessary.

In the present study, a new kinetic model is proposed to solve the Riemann problem for stiffened gas interface, in which each gas is reflected back from the fluid interface. The interface is moving with a velocity to achieve the force balance between both sides. Then this non-mixing kinetic model is applied to compute the numerical flux at a cell interface, and a new GKS for multifluid flow with stiffened EOS is developed. Typical