Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0297

Vol. **27**, No. 1, pp. 145-166
January 2020

An Improved Gas-Kinetic Scheme for Multimaterial Flows

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Received 7 November 2018; Accepted (in revised version) 14 March 2019

Abstract. The efficiency of recently developed gas-kinetic scheme for multimaterial flows is increased through the adoption of a new iteration method in the kinetic non-mixing Riemann solver and an interface sharpening reconstruction method at a cell interface. The iteration method is used to determine the velocity of fluid interface, based on the force balance between both sides due to the incidence and bounce back of particles at the interface. An improved Aitken method is proposed with a simple hybrid of the modified Aitken method (Aitken-Chen) and the Steffensen method. Numerical tests validate its efficiency with significantly less calls to the function not only for the average number but also for the maximum. The new reconstruction is based on the tangent of hyperbola for interface capturing (THINC) but applied only to the volume fraction, which is very simple to be implemented under the stratified framework and capable of resolving fluid interface in mixture. Furthermore, the directional splitting is adopted rather than the previous quasi-one-dimensional method. Typical numerical tests, including several water-gas shock tube flows, and the shock-water cylinder interaction flow show that the improved gas-kinetic scheme can capture fluid interfaces much sharper, while preserving the advantages of the original one.

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

Key words: Gas-kinetic scheme, non-mixing interface model, stiffened equation of state, improved Aitken method, tangent of hyperbola for interface capturing.

1 Introduction

The compressible multimaterial flow is of great interest due to its importance in many engineering applications. A big challenge for a CFD method to capture the instability of fluid interface and the mixing of different fluids with the requirement of numerical dissipation, resolution, conservation and robustness, especially for high Mach number

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and large density ratio [1,2]. Most existing studies are directly based on the macroscopic governing equations, such as the Euler equations, and the Riemann problem is usually solved to capture the field discontinuities for either a single fluid [3,4] or across a fluid interface [5–7]. On the basis of the mesoscopic gas-kinetic theory, different numerical scheme can also be developed, which is suitable for not only continuum flows [8] but also rarefied flows [9–11]. For multimaterial flows, different kinetic Riemann solvers have been constructed such as those based on mass fractions of ideal gas mixtures [12–14], separated transport of ideal gas species [15–18] and stiffened gases [19,20], as well as the kinetic flux vector splitting for stiffened gas [21–24].

Recently, a new kinetic model has been proposed to solve the Riemann problem for stiffened gas interface [25]. In this model each gas is reflected back from the fluid interface which is moving with a velocity to achieve the force balance between both sides. It is second-order accurate in both space and time. Different from the previous kinetic Riemann solvers, the numerical mixing at the fluid interface is eliminated, which is dominant when the grid cell size is much larger than the width of physical interface. This numerical mixing may result in pressure oscillation near the material interface or contact discontinuity, especially when using local thermodynamic equilibrium assumption [26]. Furthermore, the extension of the kinetic model to high-order accuracy and multidimensional flows is straightforward. In addition, it is also simple to take into account the viscous effect inside each fluid component.

Based on the kinetic Riemann solver and with the help of the idea of discrete equation method [27] or stratified model [28,29] for fluid mixture, the gas-kinetic scheme for multimaterial flows (labeled as GKS-MMF) has been developed and shows good performance in many typical flows [25]. The advantages of the scheme include the conservation of each component, free of non-physical oscillations near fluid interface and the robustness in the flow with strong shock waves or large density ratio. The mesoscopic description of flow guarantees the inherent capability to characterize the complicated flow structures such as shock waves and other discontinuities. Even for inviscid flow, the corresponding numerical dissipation is more consistent and natural when compared with those based on macroscopic models.

To further increase the computational efficiency, two improvements are worthy of consideration. The first one is the iteration method in the kinetic Riemann solver to determine the interface velocity where the bisection method is applied. Although it works good but the convergence rate is slow which means more computational cost for the calculation of forces on both side of a fluid interface from the distribution function. Better alternative is required to reduce the iteration number, such as the Steffensen method. The second one is the reconstruction technique to sharpen the fluid interface. It is necessary for an interface capturing method where the numerical mixing can not be avoided especially based on a fluid mixture model. The tangent of hyperbola for interface capturing (THINC) technique is a good candidate which can effectively sharpen the interface in both incompressible [30] and compressible flows [31, 32]. In the present study, the scheme is improved through these two modifications and is validated by typical tests,