§24. Basic Study on the High-Resolution Two-Fluid Simulation of Magnetic Reconnection

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Fast magnetic reconnection is a key physical process to clarify explosive phenomena in space and astrophysical plasmas such as the solar flare. The framework of (quasi-) steady resistive magnetohydrodynamics (MHD), which is the simplest model for magnetic reconnection, could not describe and explain the fast reconnection process in high magnetic Reynolds number regime. [1,2] Therefore, more detailed plasma models that include kinetic effects such as the Hall effect and the electron inertia have been intensively studied and have indicated some important roles of the kinetic effects for the fast reconnection process.[3] Recent high-resolution MHD simulations, on the other hand, revealed that the reconnection rate in the very high magnetic Reynolds number is intermittently enhanced with respect to the development of multiple secondary plasmoids in the thin Sweet-Parker-like current sheet. [4,5] However, the kinetic effects for magnetic reconnection in the very high magnetic Reynolds number have not been recognized yet.

The final objective is to elucidate the mechanism of fast magnetic reconnection in the very high magnetic Reynolds number. Particularly, in this study, we concentrate on large-scale fluid models with the kinetic effects, the Hall MHD and the full two-fluid models. High-resolution simulations for those models, however, have been difficult to realize so far because numerical methods for the models were not well developed. Therefore, as the first step, the numerical schemes for the Hall MHD and the full two-fluid equations are investigated and developed in this paper.

The Hall MHD equations can be split into the ideal MHD and the Hall terms. The Hall terms considered here are written as

$$\frac{\partial}{\partial t}\begin{bmatrix} \boldsymbol{B} \\ B^2/2 \end{bmatrix}_{Hall} + \nabla \cdot \begin{bmatrix} \boldsymbol{u}_H \boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}_H \\ B^2 \boldsymbol{u}_H - \boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{u}_H) \end{bmatrix} = 0 , \qquad (1)$$

where the Hall velocity $\boldsymbol{u}_H = -\nabla \times \boldsymbol{B}/\rho$. The second equation that is the energy correction to the ideal MHD is directly derived from the first equation. We apply the HLLD scheme [6], which is one of the best high-resolution schemes for MHD, to the ideal MHD. On the other hand, the numerical flux for the Hall terms (1) is computed by the local Lax-Friedrichs scheme.[7] Here, the spectral radius of (1) is approximately given by $u_H + \delta_i \pi B / \Delta\rho^{1/2}$, where δ_i and Δ are the ion inertia length and the grid width, respectively. A shock tube test problem is shown in Fig. 1, where δ_i is set to 0.05, 0.1, 0.2, respectively. As δ_i approaches zero, the profile is approximating to that of the MHD. Several numerical tests indicated the robustness of the present scheme. Although the electron pressure effect is ignored, the algorithm can be straightforwardly extended.

Numerical techniques for the full two-fluid equations are also investigated. The full two-fluid equations can be written as hyperbolic conservation laws with source terms, i.e., hyperbolic balance laws. The conservation laws of the ion and the electron fluid are solved using the HLLC scheme that is reduced from the HLLD scheme for MHD in the zero magnetic field limit. The Maxwell equations, which are linear hyperbolic systems, are computed by the upwind scheme. All the source terms are treated explicitly same as the conservation laws in this paper. In particular, we investigate a numerical treatment of the source term for the time evolution equation of the electric field as,

$$\frac{\partial \boldsymbol{E}}{\partial t} - \nabla \times \boldsymbol{B} = -\frac{1}{\delta_i}\left(n_i \boldsymbol{u}_i - n_e \boldsymbol{u}_e\right). \qquad (2)$$

This equation completely satisfies the Gauss's law if the Gauss's law is initially satisfied. The right side of (2) must be computed at the cell center in the present scheme. Thus, it is evaluated from algorithms (A) the ion and electron momenta at the cell center, and (B) the numerical mass fluxes of the ion and electron at the cell boundary. Basic numerical experiments such as the large amplitude plasma oscillation suggested that the source term of (2) should be computed by the algorithm (B) rather than (A) since the discrete Gauss's law of (A) is strongly violated even in one-dimension. Based on the experimental results, an efficient implicit-explicit (IMEX) time integration method for the full two-fluid systems is under development.

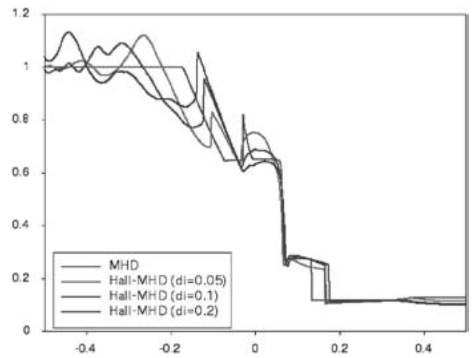

Fig. 1. The density profile of Brio-Wu shock tube test problem for the Hall MHD. δ_i is 0.05 (green), 0.1 (blue), 0.2 (purple), respectively. The result of the ideal MHD is also plotted (red).

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