High-order two-fluid plasma solver for direct numerical simulations of plasma flows with full transport phenomena

Z. Li, zhaorui.li@tamucc.edu
D. Livescu, livescu@lanl.gov

The two-fluid plasma equations with full transport terms have been implemented in the CFDNS code and solved by using sixth-order non-dissipative compact finite differences for plasma flows in several different regimes [2]. In order to be able to fully resolve all the dynamically relevant time and length scales, while maintaining computational feasibility, the assumptions of infinite speed of light and negligible electron inertia have been made. The accuracy and robustness of this two-fluid plasma solver in handling plasma flows in different regimes have been validated against four canonical problems: Alfven and whistler dispersion relations, electromagnetic plasma shock, and magnetic reconnection. For all test cases, by using physical dissipation and diffusion, with negligible numerical dissipation/diffusion, fully converged Direct Numerical Simulations (DNS)-like solutions are obtained when the ion Reynolds number based on grid size is smaller than a threshold value which is about 2.3 in Ref. [2].

Background and Motivation

Modeling and simulation of plasma flows have been attracting increasing attention among the plasma community due to its importance to a large variety of applications including fusion, space physics, industry, astrophysics, and so on. However, even with the advancements in computational power, accurate simulations of plasma flows in many practical problems of interest, such as the study of hydrodynamic instabilities in the Inertial Confinement Fusion (ICF) coasting/deceleration stage, are still scarce. A major reason is the lack of affordable plasma models that can accurately capture all plasma phenomena over a broad range of time and length scales.

In contrast to the kinetic models that solve the six-dimensional Boltzmann equation coupled with Maxwell equations, for collision-dominated plasma flows, fluid models developed by using the continuum approximation become computationally feasible because the governing equations solved in the fluid models are three-dimensional. The single-fluid magnetohydrodynamic (MHD) models (e.g. ideal and resistive MHD) have been successfully used for studying large-scale plasma flows but fail to describe plasma phenomena that occur on a length scale comparable to or smaller than the ion skin depth. While the two-fluid plasma models and Hall-MHD equations can solve many of the problems encountered in single-fluid MHD by considering the two-fluid effects, previous applications of the two-fluid models did not include full plasma transport terms and usually relied on the numerical dissipation/diffusion to obtain stable solutions. Such solutions can become corrupted by numerical artifacts and generally might misrepresent the physical transport phenomena which are particularly important in some problems of interest. For example, in the ICF deceleration stage, the heat flux and viscous dissipation terms should have significant impact on the development of hydrodynamic instabilities and late-time turbulence.

Methodologies

The computational feasibility of the two-fluid plasma solver is achieved by applying the infinite speed of light and negligible electron inertia assumptions, which can be well justified for many problems of interest such as the ICF deceleration stage, into the Branginskii's two-fluid plasma model [1]. Using these two assumptions limits our interests to plasma phenomena whose characteristic frequency (ω) is much smaller than the electron plasma frequency (ω_{pe}) and electron cyclotron frequency (ω_{ce}). Therefore, the severe

High-order two-fluid plasma solver for direct numerical simulations of plasma flows with full transport phenomena

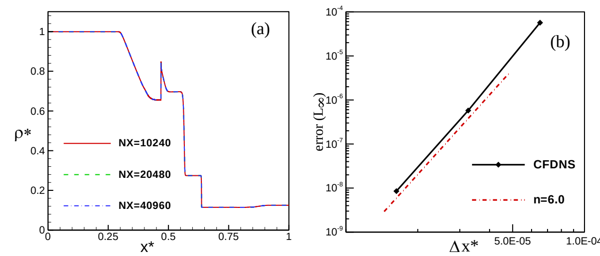
time-step limitations caused by high-frequency waves are eliminated.

The advantage of the two-fluid plasma solver in accurately capturing physics of plasma flows is further achieved by implementing full plasma transport terms, including temperature and magnetic field dependent ion and electron viscous stresses and heat fluxes, frictional drag force, and ohmic heating terms, and solving the two-fluid plasma equations by using the sixth-order non-dissipative compact finite differences at sufficiently fine grid resolutions. In addition, by using the full directional dependence of the physical transport with respect to the magnetic field, for the first time, the the role of anisotropic transport on plasma flows can be studied.

Main Results and Conclusions

The numerical results for the four canonical problems show that, by varying the characteristic/background number density, length scale, temperature, and magnetic strength, the ideal, resistive, and Hall MHD solutions can be recovered from the two-fluid plasma simulations, as limiting cases, in regimes where the non-dimensional parameters satisfy the corresponding conditions described in Ref. [2].

For all test cases, because of the inclusion of the physical transport terms and the employment of a high-order non-dissipative compact scheme in the two-fluid plasma solver, fully converged DNS-like solutions are obtained at all Reynolds numbers, provided the ion grid Reynolds number ($Re_{\Delta} = Re^i/NX$) is smaller than a threshold value. As an example, Fig. 1 (a) shows that, at ion Reynolds number, $Re^i \approx 2.3 \times 10^4$, all plasma shock characteristics can be fully resolved at grid resolutions satisfying $Re_{\Delta} \leq 2.3$ condition. Near the sharp gradients in the plasma shock, in contrast to the first-order convergence rate commonly found in studies using shock-capturing schemes, the grid convergence rate calculated from Fig. 1 (b) is $\hat{n} \approx 6.08$ which is very close to the theoretical value of the sixth-order compact scheme.



(a) Fully converged density profile at different resolutions and (b) comparison of the grid convergence rate calculated by two-fluid plasma solver with the theoretical limit of the sixth-order compact scheme. The simulations were conducted for plasma shock with $Re^i \approx 2.3 \times 10^4$.

For the magnetic reconnection problem, the magnetic flux saturation time and value predicted here are in good agreement with those reported in previous studies under similar conditions. In addition, the numerical results show that the magnetic flux saturation time and value converge when the ion and magnetic Reynolds numbers are large enough. Thus, the DNS-like results become relevant to practical problems with much larger Reynolds numbers.

Acknowledgements

Los Alamos Report LA-UR-19-20694. This work was made possible in part by funding from the LDRD program at the Los Alamos National Laboratory through Project No.20150568ER. Z. Li was supported by the Los Alamos National Laboratory, under Grant No.430461. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

References

[1] S. I. Braginskii. Transport processes in a plasma. *Rev. Plasma Phys.*, 1:205–311, 1965.

[2] Z. Li and D. Livescu. High-order two-fluid plasma solver for direct numerical simulations of plasma flows with full transport phenomena. *Phys. Plasmas*, 26:012109, 2019. *Editor's Pick.*