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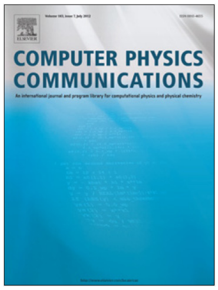

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Fully-implicit finite volume method for the ideal two-fluid plasma model

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Abstract

We present a novel numerical model that simulates ideal two-fluid plasmas coupled to the full set of Maxwell's equations with application to space and laboratory plasmas. We use a fully-implicit finite volume method for unstructured meshes, that uses an advection upstream splitting method (i.e., AUSM$^+$-up) for all speeds to discretize the numerical fluxes of the fluids. In addition, we discretize the Maxwell's equations with a modified-Rusanov scheme. The electromagnetic numerical dissipation is scaled using the scales of the fluid-electromagnetics coupled problem that are found to be very different from those of the uncoupled problem. Our numerical scheme guarantees that the elliptical constraints of the Maxwell's equations are satisfied by using hyperbolic divergence cleaning. We validate the performance and accuracy of our model by simulating the following conventional cases: a circularly polarised wave, a Brio-Wu type shock tube, and a two-fluid plasma reconnection with the GEM challenge set up. Our model reveals the complexity of the two-fluid model compared to magnetohydrodynamics (MHD) models, as the inclusion of charge separation, the displacement current and the electron dynamics present are ignored by the MHD simplifications. The two-fluid model shows the presence of electromagnetic and plasma waves and the effect that they have in even the simplest cases. We also compare our model to other available two-fluid models and find our results to be in good agreement.

Keywords: Plasma, Finite Volume Method, Magnetohydrodynamics (MHD), Multi-fluid

1. INTRODUCTION

The complex interaction between the charged particles and the electromagnetic fields that are present in a plasma results in a behaviour very different from gases. The microscopic state of a plasma can be characterized by the Boltzmann equation that describes the evolution in time of the distribution function of the different species of particles in the six-dimensional phase space. If there are enough collisions between the particles, the kinetic description can be reduced to a fluid model by taking moments of the Boltzmann equation. Collisions bring the fluids to local thermal equilibrium, which means that their distribution function is Maxwellian. However, owing to the difference between the electron and ion masses, the various type of collisions are not equally efficient in exchanging momentum and energy [1, 2]. For this reason, ion and electron fluids can remain in a different local thermal equilibrium, characterized by different average velocities and temperature. After enough time, the velocities and temperatures will tend to equilibrate. Conversely, if the macroscopic time scale related to the free-flow and electromagnetic processes τ_H is of the same order as the equilibration time τ_{eq}, the two-fluid description is necessary. In mathematical terms, the condition for the two-fluid regime is $\tau_H \sim \tau_{eq} \gg \tau_i \gg \tau_e$, where τ_i and τ_e are the collisional relaxation times of ions and electrons, respectively. The study of the dynamics of plasmas in electromagnetic fields is fundamental in a wide number of fields: astrophysics, nuclear fusion plasmas, electrical propulsion, hypersonic flows, electrical discharges, etc [3].

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