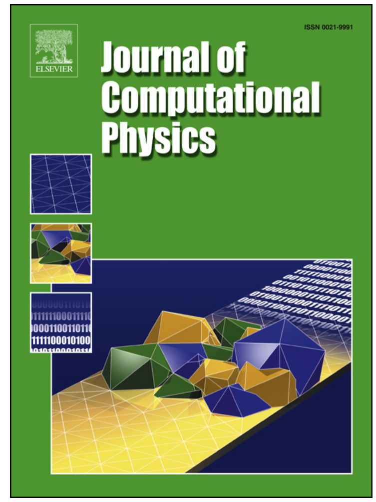

Structure-preserving operators for thermal-nonequilibrium hydrodynamics

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Structure-preserving operators for thermal-nonequilibrium hydrodynamics

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Abstract

Radiation hydrodynamics simulations based on a single fluid two-temperature model may violate the law of energy conservation, because the governing equations are expressed in a nonconservative formulation. In this study, we maintain the important physical requirements by employing a strategy based on the key concept that mathematical structures associated with conservative and nonconservative equations are preserved, even at the discrete level. To this end, we discretize the conservation laws and transform them using exact algebraic operations. The proposed scheme maintains global conservation errors within the round-off level. In addition, a numerical experiment concerning the shock tube problem suggests that the proposed scheme agrees well with the jump conditions at the discontinuities regulated by the Rankine–Hugoniot relationship. The generalized derivation allows us to employ arbitrary central difference, artificial dissipation, and Runge–Kutta methods.

Keywords: Radiation hydrodynamics, Nonequilibrium hydrodynamics, Conservative scheme, Structure-preserving scheme

1. Introduction

Radiation hydrodynamics (RHD)[1] is one of the widely used techniques employed in laser-plasma simulations. In RHD, a neutral charge is assumed for a fluid composed of ions and electrons. This assumption allows large-scale plasma simulations to be performed, as the grid interval is not limited by the Debye length, unlike the conventional particle-in-cell (PIC) method. This type of simulation has been employed in laser-plasma simulations that model, for example, the implosion dynamics of inertial confinement fusion (ICF)[2].

One of the most simplified RHD simulations combines radiative transfer and one-temperature hydrodynamics, which are employed by the FastRad3D code[3]. However, a thermal nonequilibrium typically exists between the ions and electrons of a laser plasma. The incident laser is absorbed by the inverse Bremsstrahlung process, and the energy is deposited on the electrons. Thus, the single fluid two-temperature (1F2T) model is employed to investigate plasma hydrodynamics more accurately [4, 5, 6]. The governing equations of the 1F2T model (excluding viscous and heat conduction effects) are expressed in the form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + p_{\mathrm{i}} + p_{\mathrm{e}}) = 0, \tag{2}$$

$$\frac{\partial \rho e_{\mathrm{i}}}{\partial t} + \nabla \cdot (\rho e_{\mathrm{i}} \mathbf{u}) + p_{\mathrm{i}} \nabla \cdot \mathbf{u} = 0, \tag{3}$$

$$\frac{\partial \rho e_{\mathrm{e}}}{\partial t} + \nabla \cdot (\rho e_{\mathrm{e}} \mathbf{u}) + p_{\mathrm{e}} \nabla \cdot \mathbf{u} = 0, \tag{4}$$

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