Lattice-Boltzmann Models of Ion Thrusters

by
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The lattice-Boltzmann method (LBM) is to be applied to modeling the flow in electric propulsion (EP) systems such as ion thrusters. Specifically to be investigated are issues that affect ion thruster operation like the back-flow that reduce engine life. Historically, the transport of mass, momentum, energy, sub-atomic particles, etc. and the complex multi-scale physics involved, have been modeled using Monte Carlo methods a la Bird. While techniques such as the Direct Simulation Monte Carlo (DSMC) have achieved great success in EP models, their connection to the Boltzmann equation for the molecular velocity distribution function suggests alternate approaches based more directly on that equation.

To model an EP system with the lattice-Boltzmann method, the Boltzmann equation is coupled with an electric field in as simple a form as $\partial_t f + \boldsymbol{\xi} \cdot \boldsymbol{\nabla} f + q\,(\boldsymbol{E}/m) \cdot \boldsymbol{\nabla}_{\boldsymbol{\xi}} f \;=\; Q(f,\,f), \boldsymbol{E} = -\boldsymbol{\nabla}\phi, \epsilon_0 \boldsymbol{\nabla}^2 \phi \;=\; e \iint f d\boldsymbol{\xi} \,-\, \rho_0$ where ϕ is the electrostatic potential that yields the electric field $\boldsymbol{E}$, m is the mass of a molecule, q is the associated charge, and ρ_0 is the charge density due to oppositely charged species that are not necessarily explicitly simulated. It is a goal of this research to implement the EP system model with LBM to explore the possible lower computational cost of the collisional and streaming steps and determine their computational benefits in this case. The typical EP number densities imply Knudsen numbers (Kn) that are much different from the $Kn \approx 1$ of the usual LBM. However, EP systems have been modeled with $Q(f,\,f) = 0$ i.e., no collision as in a collision-less plasma driven by the electric field, and linear BGK-type collisions for large numbers of particles. This same linear form occurs in a model of charge exchange collision (CEX) between beam ions and neutral gas that can produce slow ions that can impact thruster grid surfaces. The linear collisions may be modeled via $Q(f,\,f) = \nu(n,\,T)(f_0 - f)$ where $\nu(n,\,T) = 4n\sigma\sqrt{kT/\pi m}$ and $T = m(< v^2 > - < v >^2)/3k$. These forms are more amenable to modeling with LBM. However, the coupling of electromagnetic and thermal effects may negate some of the benefits of the simplicity of the LBM algorithm (i.e., being coupled to elliptic equations) - but that would occur with other schemes. The simulations are compared to similar DSMC.