Towards Multidimensional Hybrid-Kinetic Modeling of Thermionic Hollow Cathodes

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Background

• Thermionic hollow cathodes (THCs) are general purpose plasma sources used in a variety of applications.
• THCs are a critical component of Hall and ion thrusters, where they serve as an electron source for both neutralization and ionization.
• Direct kinetic (DK) methods are a class of simulation techniques which directly solve the Boltzmann equation in discretized phase space. These methods are able to capture non-equilibrium behavior without the statistical noise of particle methods.

Motivation

• The operation of THCs is poorly understood. Upon the plasma’s expansion to the plume, instabilities occur that cause deviations from classical theory.
• With the advent of magnetically shielded Hall thrusters, the erosion of THCs has become a life-limiting factor of chief concern.

Methods

• An axisymmetric domain is assumed (2D3V). The neutral particle solver is detailed here. Collisions are neglected in this work.
• Taking advantage of the circular characteristics in the \((v_r, v_\theta)\) plane of cylindrical coordinates, the hyperbolic PDE is:
  \[
  \delta_t r f + v_r \delta_r r f + \xi \cos \omega \delta_r r f - \xi \delta_w (\sin \omega f) = 0
  \]
  where \((v_r, v_\theta) = (\xi \cos \omega, \xi \sin \omega)\) and \(f\) is the VDF value.
• A finite volume scheme is adopted for this code. Space, time and velocity are solved discretely via the following methods:
  o Spatial advection: 2nd order MUSCL scheme,
  o Velocity advection: 2nd order centered differencing scheme,
  o Temporal integration: 1st order forward Euler scheme.

Results

• To benchmark the neutral solver, simulations are carried out for a simple expansion flow and compared with the validated DSMC code, MONACO.
  The test case has the following properties:
  o 1) inflowing Xenon at 300K, \(U = 100\ m/s\),
  o 2) diffuse walls at 300K,
  o 3) symmetry,
  o 4) outflow.
• Figures 2, 3 & 4 compare the bulk properties of particle density, radial velocity, and axial velocity, respectively.

Discussion

• Overall agreement of the particle and continuum kinetic methods is shown to be qualitatively good. The greatest divergence is at \(r = 0\).
• The Vlasov scheme does not conserve radial momentum. This causes a radial drift at the centerline in Figure 3, which lowers the density at the centerline, as in Figure 2.
• The Lorentz force breaks the circular characteristics and thus makes this scheme invalid for ions. Therefore, a different scheme must be implemented for ions.

Conclusions & Future Work

• A new, direct kinetic solver has been implemented and benchmarked with the DSMC code MONACO. Results show good agreement, despite an erroneous radial drift at the centerline.
• Better stability and accuracy could be achieved through a higher order temporal scheme. Collisions may help agreement of results.
• An axisymmetric fluid electron algorithm and ionization will be introduced in order to add plasma to the simulation.
• This algorithm will eventually be applied to study non-equilibrium processes in the THC plume to better inform cathode lifetime estimates and instability suppression techniques.

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