Towards Multidimensional Hybrid-Kinetic Modeling of Thermionic Hollow Cathodes

Alexander R. Vazsonyi & Iain D. Boyd | University of Michigan | 9th Annual MIPSE Symposium

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_θ) plane of cylindrical coordinates, the hyperbolic PDE is:

$$\delta_t rf + v_x \delta_x rf + \xi cos\omega \delta_r rf - \xi \delta_w (\sin(w)\, f) = 0$$

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:
  - Spatial advection: 2nd order MUSCL scheme,
  - Velocity advection: 2nd order centered differencing scheme,
  - Temporal iteration: 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:

- **1)** inflowing Xenon at 300K, U = 100 m/s, n = 1e20 (m-3),
- **2)** diffuse walls at 300K,
- **3)** symmetry,
- **4)** outflow.

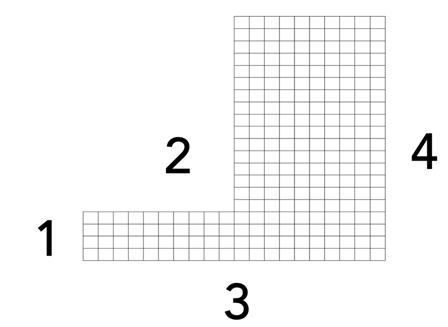


Figure 1: Simulation Domain

- Figures 2, 3 & 4 compare the bulk properties of particle density, radial velocity, and axial velocity, respectively.

Figure 2: Comparing Densities (L: DSMC, R: Vlasov)

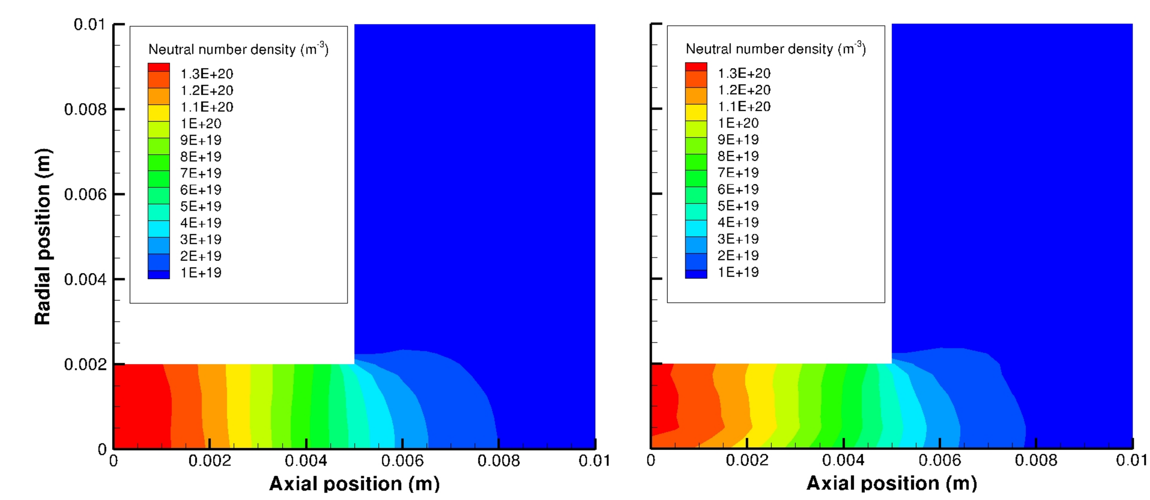


Figure 3: Comparing Radial Velocities (L: DSMC, R: Vlasov)

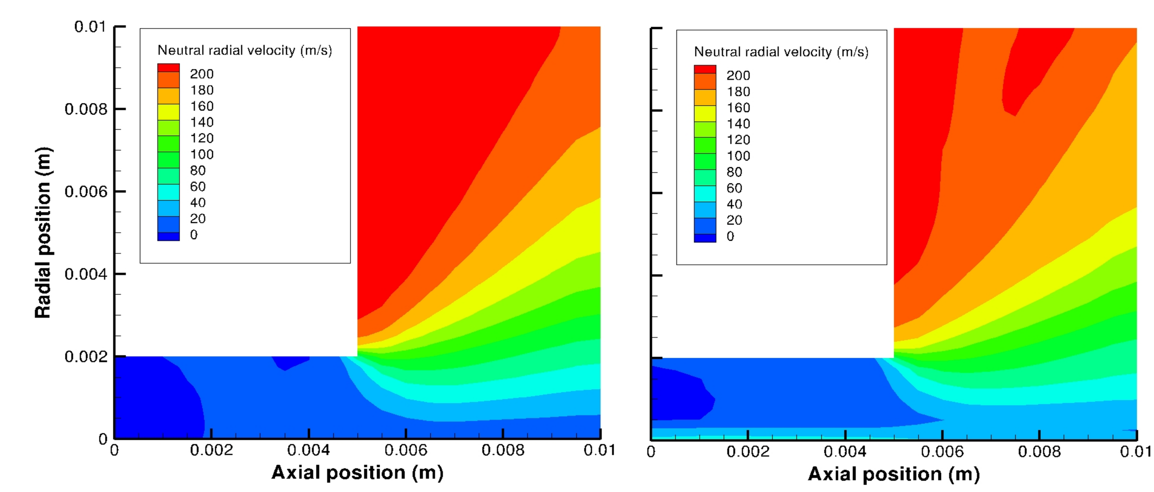
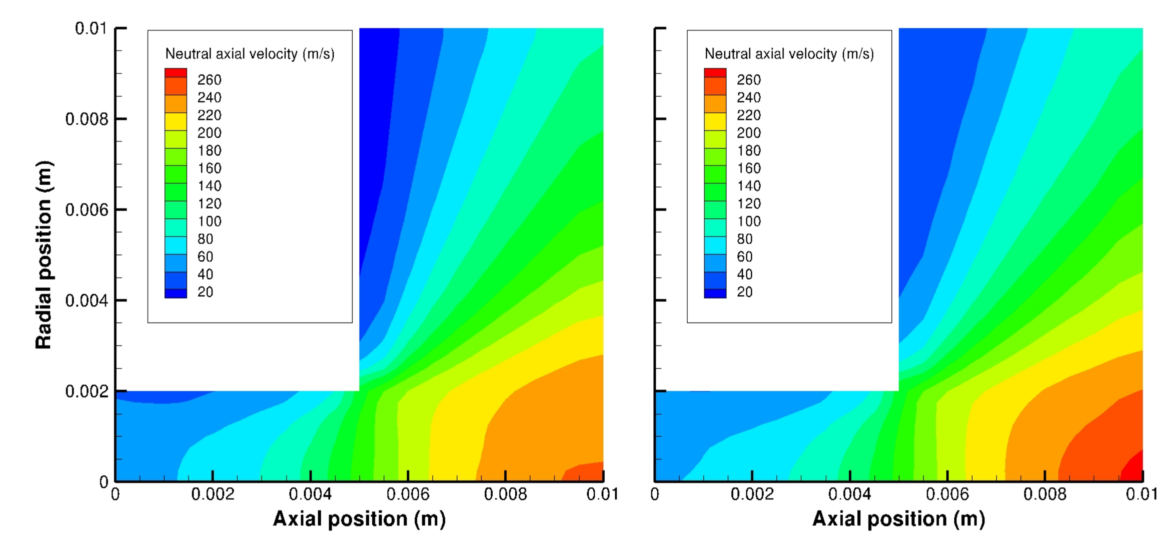


Figure 4: Comparing Axial Velocities (L: DSMC, R: Vlasov)



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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