Plasma Energy Conversion in the Expanding Magnetic Nozzle

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Abstract: Plasma flow control and energy conversion in the expanding magnetic nozzle are numerically investigated based on a supersonic helicon-type source in order to find the interplay between charged particles and sectional induced fields. Ion axial velocity development is clearly observed as well as the axial momentum growth under different conditions of applied magnetic field intensity and initial ion energy. The maximum rate of ion axial momentum increase is scaled to 3-4 times of its original value at the exit. During the overall convergence of the particle-in-cell model, the average ion kinetic energy arises while the average electron kinetic energy diminishes. It should be noted as the superiority of this fully kinetic simulation in the non-equilibrium and non-uniform situations that various degrees of magnetization and accompanying local electrostatic acceleration are deduced to jointly direct the energy transfer towards heavy-mass low-speed ions. Electric energy over the whole region is shown greater in the stronger 0.4T magnetic nozzle than in the 0.1T one. However, the distributions of electron velocity seriously deviate from the theoretical Maxwellian function, which according to the calculated cases for initial kinetic energy of 10eV, the statistical curves are even seen varying within the system axial space.

I. Introduction

Plasma confinement in many applications has been achieved via the longitudinal applied magnetic fields, as they create magnetic nozzles partly comparable to magnetic mirrors or solid de Laval nozzles.[1, 2] In space electric propulsion, particularly, the purpose of a slowly diverging magnetic nozzle (SD-MN) is to control the plasma plume expansion, wherein the axial plasma momentum greatly contributes to macro device performances. Physical processes within a general magnetic nozzle correlate with complex interactions between electromagnetic fields and charged particles, by which the beneficial energy conversion and subsequent formation of axial ejection may be realized exactly. Thereby, to some extent, a magnetic nozzle can be recognized as an energy conversion device since its intrinsic mechanisms resemble those involved in astrophysical jets, magnetospheric physics, thermonuclear fusion etc., as well.[3-5]

The application of an expanding magnetic nozzle assists in plasma acceleration where plasma non-direct energy is partly converted into direct kinetic energy. Taking electric plasma propulsion for instance, applications of the magnetic nozzle are roughly similar, but varying from specific devices.[6-8] Generally, it has been investigated by previous study that the geometric configuration as well as plasma characteristics impact on performance of the magnetic nozzle.[9-11] Changing the axial location of applied magnetic field or initial radius of plasma bunch can greatly alter the exhaust flow, while some comments on plasma acceleration and detachment processes also

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highlighted the influence from current-induced magnetic field. It should be worth noting that the plasma azimuthal currents contribute significantly to SD-MNs, especially the part based on electron Hall currents of an opposite direction to the solenoid coil currents.[12, 13]

Basically, both the aerodynamic effects and electromagnetic forces are of interest in magnetic confinement of high-speed plasma.[14] It is the electrostatic potential gradient and current-magnetic field inducement that mostly guides the energy conversion process among several different being forms. Notice that the local separation effects from the non-equilibrium of magnetization as well as ambipolar diffusion probably force the fast moving electrons dragged by low-speed ions. Thereby a fully kinetic particle model is quite required here, without assumptions such as quasi-neutrality or complete magnetization in plasma study. The process of charge separation induces the formation of sectional electrostatic field, by means of which the energy of charged particle is transferring between each other. Other predominant phenomenon from the local effects within an expanding magnetic nozzle is that the electron velocity distribution may deviate far from the theoretical Mawellian function. Those curve shapes may largely depend on the degree of plasma magnetization, as well as specific plasma parameters.

The discussions presented in this paper are derived from a two-dimensional particle-in-cell (PIC) model of a collisionless fully-ionized argon plasma flowing through the expanding magnetic nozzle. Our option for this kinetic simulation approach is to examine the details in plasma-field interacting motion straight-forwardly, comparing to the most previous fluid models. The calculated plasma condition after the exhaust of a helicon-type source is employed in each simulation case and comparisons are made in terms of ion axial momentum, particle kinetic energy, electrostatic field energy, and electron velocity distribution. All quantified profiles and curves of physical parameters provide close relations between electrons and ions, as well as between induced fields and charged particles. As a function of applied magnetic field strength, simulation results of the axial momentum and electron velocity are also demonstrated here.

II. Model Description and Simulation

The focus of this work is on the energy variation inside a SD-MN using the PIC procedure. In Ref. 15 a correlative model has been described and many performance properties of a MPD-type thruster have been examined. Hence a short summary is given here and some relevant characteristic changes are chiefly stressed as well. All comparisons made from calculated results along with the relevant discussions are also gathered in this section.

A. Expanding Magnetic Nozzle

As shown in Figure 1, a slowly diverging magnetic field is produced by a set of solenoid coils, which represents the typical SD-MN configuration. The magnetic field strength in this model varies from 0.1T to 0.4T by adjusting the coil current value. Argon plasma flow input into the simulation region is derived from a helicon-type source of an average electron temperature 5eV. Other major initial parameters are listed as: the plasma radius 0.025m, plasma number density 10^{16}-10^{18}m^{-3}, coil radius 0.1m, ion kinetic energy 10eV, 20eV, and 80eV, respectively.

To display the action of an expanding magnetic nozzle, a full kinetic PIC model is employed so that both non-equilibrium effects and non-Maxwellian energy and velocity distributions are available.[16] Predicted values on plasma property from the input parameters have shown that electrons are highly magnetized while ions are of different cases. At the exit of plasma flow, where could be set as the start point, an overall thrust of system is estimated on the mN order of magnitude.

Individual particles are injected according to the half-Maxwellian velocity distribution while the initial plasma number density follows the Gauss function radially. The applied external magnetic field is pre-calculated as the converging-diverging profile by an engineering method. Both induced magnetic and electric fields are updated in step during the whole PIC cycling and governed by the Maxwell's equations. Also, note that all field parameters are time-independent.

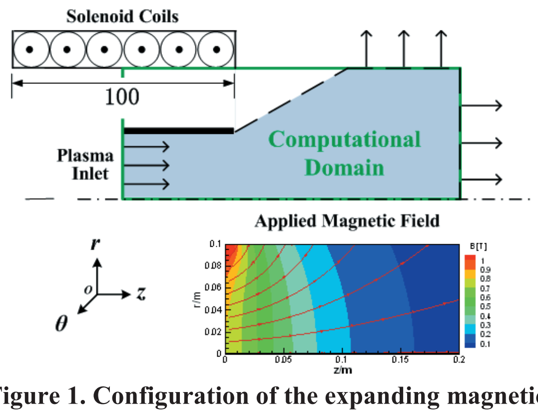


Figure 1. Configuration of the expanding magnetic nozzle.

B. Axial Momentum Growth

The typical simulation maps of plasma density and velocity provide spatial variation and inside physical process along with its flow. Shown by Figure 2, the axial velocity of ions gradually increases downstream, particularly in the vicinity of the axisymmetric center-line. This tendency clearly reflects the confinement and acceleration of plasma flow via the magnetic nozzle effects, which may also be seen in Figure 3 as the plasma axial momentum increases globally. Values of these curves are obtained from the corresponding comparisons to the original axial momentum states from the very beginning. The maximum growth is reached in the 0.4T magnetic nozzle with an initial ion kinetic energy of 80eV (high). However, it is not the same situation with regard to the initial ion energy of 10eV (low) that the largest axial momentum growth exists in the 0.2T magnetic nozzle eventually. It seems that the moderate intensity of applied magnetic field benefits more for ions flowing at a relatively low speed.

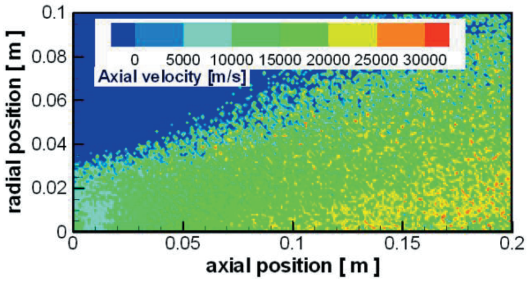


Figure 2. Contour map of ion axial velocity in the 0.4T magnetic nozzle.

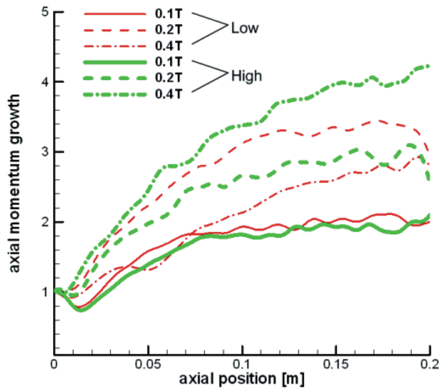


Figure 3. Axial momentum growth as a function of applied field. Thin red lines denote low ion energy and thick green lines denote high ion energy.

C. Particle Energy Evolution

Recording the energy evolution under each simulation condition, it is found that the whole system energy slightly drops along with the foregoing millions of steps and then it holds the line to the final quasi-steady state. As plotted in Figure 4, the calculation case of an initial ion kinetic energy is set as 80eV and the total magnetic field appears to be around 0.2T. The energy variations of a single charged particle show as two opposite trends in a period. The ion average energy gradually grows to some extent, which indicates the energy conversion from other parts of the system.

A possible way delivering the energy into ions is via the local electrostatic field. Due to the difference of magnetization degree, positive-charged particles with heavy mass moves slow and along separative routes from those fully magnetized electrons. As a result, the quasi-neutrality condition cannot conserve everywhere within the plasma flow. Afterwards the induced ambipolar field from charges separation comes into being. Eventually, the fast moving electrons are dragged by slow ions and kinetic energy is thereby added into ions during this local process.

To spot the time-variations of energy conversion process, the electric potential energy density is scaled as $0.5\varepsilon_0|E|^2$ and the particle kinetic energy density is scaled as $0.5nm|v|^2$. Drawn by Figure 5, both the 0.1T and 0.4T magnetic nozzles are numerically tested through an initial 20eV plasma flow. It can be seen from the curves that such two forms of energy correlate close to each other with a similar evolution tendency. Also, energies of 0.4T SD-MN show relatively larger than those of 0.1T SD-MN, which reveal that the stronger induced local effects, the higher kinetic energy density in the vast area of the expanding magnetic nozzle.

D. Electron Velocity Distribution

Strong local effects of plasma within the expanding magnetic nozzle lead to the non-equilibrium state of released particles. Even for highly mobile electrons, no single temperature may be kept, namely that the theoretical Mawellian velocity distribution function cannot guarantee all the time. From the statistical results of Figure 6 and Figure 7, electron velocity distribution lines of one or two summits possibly occur and vary with the applied magnetic field intensity as well as the initial ion energy. Note that the overall distribution of electron velocity presents the single-summit feature if the initial ion energy assumed low. Meanwhile, these distribution lines at different axial positions are moving into various shapes probably as a result of the joint effects from local electromagnetic fields. In addition, comparing the electron velocity curves of Figure 6(b)(c) and Figure 7(b)(c), the significant difference exists in the most widespread range of the bulk electron velocity. The plasma flow of higher initial ion energy (20eV or 80eV) likely forms into a spatial uniform distribution easier by the fixed SD-MN, whereas these curves shape differently between the 0.1T and 0.4T magnetic conditions. Discussions on electron velocity distribution can reveal the inevitable influence from the inter-particle energy transfer, which in turn provide a better understanding of the intrinsic processes as well.

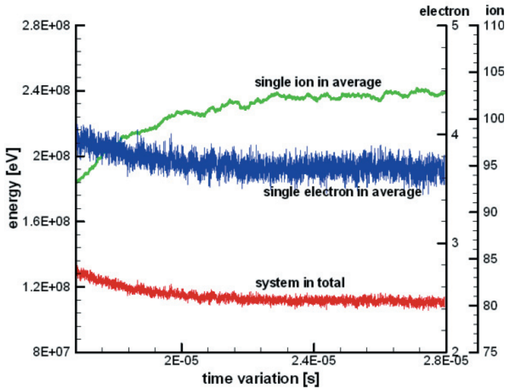


Figure 4. Single particle energy and total system energy varying with time.

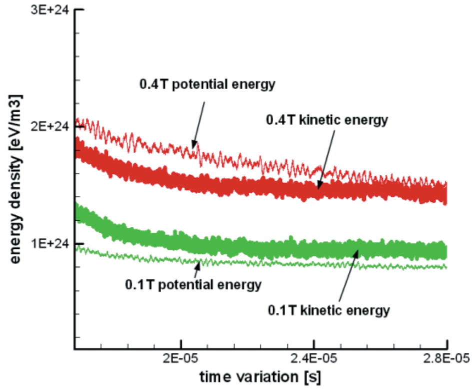
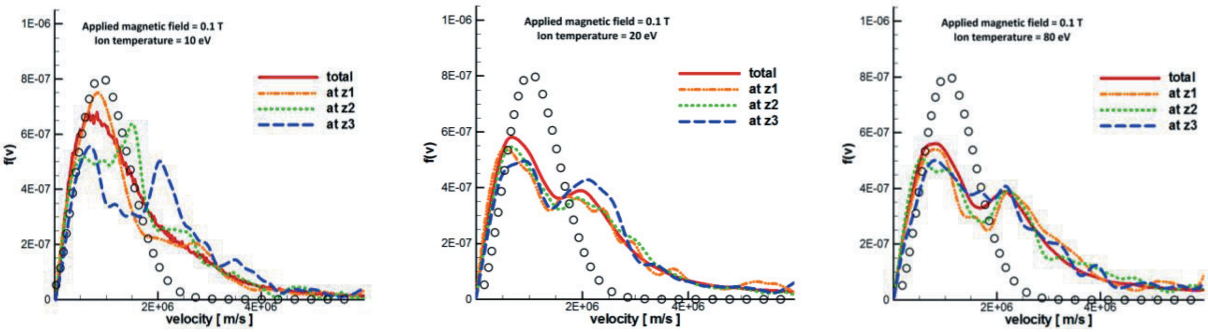
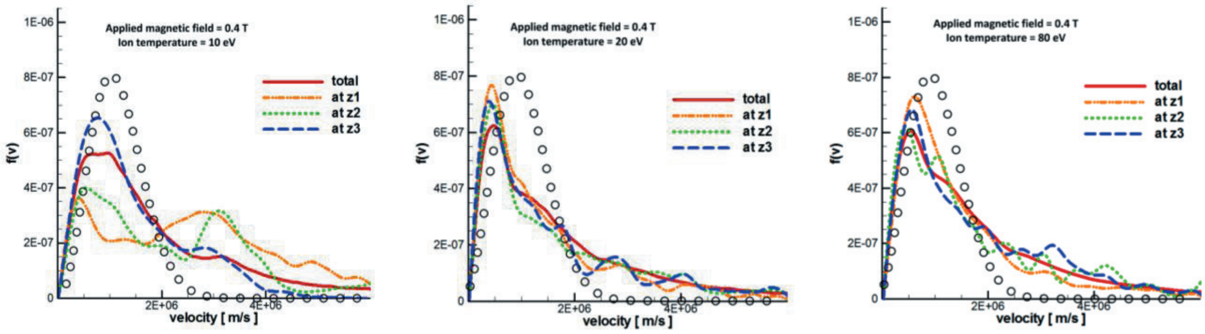


Figure 5. Plasma kinetic and electric potential energy density varying with time.



(a) (b) (c)

Figure 6. Electron velocity distribution in the 0.1T magnetic nozzle. Theoretical curve is shown by circles.



(a) (b) (c)

Figure 7. Electron velocity distribution in the 0.4T magnetic nozzle. Theoretical curve is shown by circles.

III. Conclusion

The role of an expanding magnetic nozzle in many types of plasma systems is to control the exhaust flow and utilize the propulsive force produced by heavy-mass ions moving against the vacuum space of an applied magnetic field. In this work, a two-dimensional kinetic PIC model is built and a collision-less fully ionized argon plasma flow is numerically tested. Along the way outward from the SD-MN, ion axial velocity increases, predominantly downstream in the vicinity of the system central axis. The ion axial momentum growth is scaled up to 3 times of its original value for plasma with a low initial energy flowing by the 0.2T magnetic nozzle, and 4 times for the higher initial energy and 0.4T magnetic field conditions. One notable phenomenon during the system overall energy convergence is that the average kinetic energy of a single ion relatively arises while the electron kinetic energy diminishes. It should be considered as the major reason for energy conversion that the non-equilibrium magnetization environment and local charges separation contributes mostly. Since mobile electrons of high speed strictly follow the curving lines of magnetic field, slow ions are pulled by them via an induced electrostatic field. The potential energy density of the 0.4T SD-MN is shown greater than that of the 0.1T SD-MN, meanwhile the electric field energy almost varies along with the plasma kinetic energy. Moreover, electrons deviated from Maxwellian energy distribution are seriously impacted by the various magnetic and kinetic conditions. A uniform distribution style along axial drawing can be seen in cases of 20eV or 80eV initial plasma energy. Whereas for the magnetic nozzles of 0.1T and 0.4T, plasma flow of an initial energy 10eV displays spatial varying distribution curves.

Acknowledgments

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