Computational Studies of Magnetic Nozzle Performance

IEPC-2013

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I. Introduction

Advanced electric propulsion methods currently being developed include those that incorporate a strong guiding magnetic field in a component known as a magnetic nozzle, which controls plasma flow in order to optimize the balance between specific impulse and thrust. Among the propulsion systems that will utilize magnetic nozzles are the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), magnetoplasmadynamic engine and helicon thrusters. Magnetic nozzle technology is attractive because it provides a means for avoiding contact between hot plasma and material walls, while allowing for either high thrust or high specific impulse operational modes. Magnetic field configurations may also be varied, enabling operation of plasma engines in an optimal thrust and specific impulse balance suited for different spaceflight periods.

The function of magnetic nozzles is similar to that of de Laval nozzles with both devices generating thrust through the conversion of an internal energy of a fluid to a directed kinetic energy. However, the physics of thrust generation processes are very different between de Laval nozzles, which direct flow through a physical wall, and magnetic nozzles, which direct flow through a guiding magnetic field. A schematic comparing a de Laval nozzle to a magnetic nozzle is shown in Figure 1. In this figure P, B, I, and J are the pressure, magnetic field, loop current, and current density respectively.

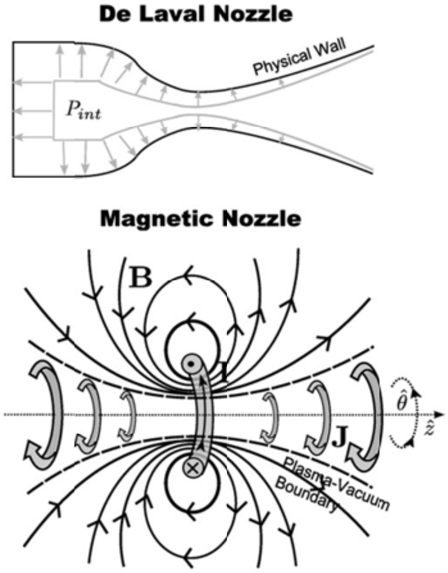

Figure 1. Comparison of a De Laval and a magnetic nozzle.

Thrust generation in a magnetic nozzle requires energy conversion from gyrokinetic energy to axial kinetic energy, giving momentum to the spacecraft by detaching plasma from initially closed magnetic field lines. Each step in this process can be achieved by a number of physical mechanisms. What these dominant physical mechanisms are is an open question which must be thoroughly addressed in order to optimize magnetic nozzle design for plasma thruster applications.

We approach this problem from a computational perspective utilizing advanced magnetohydrodynamics (MHD) solvers to study the flow of plasma in a magnetic nozzle. Our computational methods include both steady state and time accurate solvers on 2½ D axisymmetric and 3D Cartesian grids. Our studies strive to reproduce experimental results as well as possible and to provide further insight on all factors that may be needed to optimize magnetic nozzle performance. Here, we will outline our current progress in this study and discuss planned future work.

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II. Approach

To study magnetic nozzle physics we employ a generalized Ohm's law MHD solver. A standard form of the generalized Ohm's law is

$$\boldsymbol{E} = -\boldsymbol{U} \times \boldsymbol{B} + \frac{1}{n_e q}\boldsymbol{J} \times \boldsymbol{B} - \frac{1}{n_e q}\nabla(n_e k T_e) + \frac{\boldsymbol{J}}{\sigma} \quad . \qquad (1)$$

The terms on the right of Equation 1 are the convective, Hall, electron pressure, and resistive terms, respectively. Previous efforts in studying magnetic nozzle physics with MHD methods have focused on ideal and resistive MHD solvers that incorporate only the convective and resistive terms in Ohm's law. Inclusion of the Hall and electron pressure terms, in addition to the conventional resistive term, enables our advanced MHD model to capture the physics of ion demagnetization and thermoelectric effects respectively. Use of the generalized Ohm's law given above is essential to capture important physics of magnetic nozzle operation and fulfills a current gap in the study of magnetic nozzle physics.

III. Current Progress and Future Work

An extensive literature review of magnetic nozzle research has been performed, examining previous work, as well as a review of fundamental principles. This has allow us to catalog all basic physical mechanisms which we believe underlie the thrust generation process. Energy conversion mechanisms include the approximate conservation of the magnetic moment adiabatic invariant, generalized hall and thermoelectric acceleration, swirl acceleration, thermal energy transformation into directed kinetic energy, and Joule heating. Momentum transfer results from the interaction of the applied magnetic field with currents induced in the plasma plume., while plasma detachment mechanisms include resistive diffusion, recombination and charge exchange collisions, magnetic reconnection, loss of adiabaticity, inertial forces, current closure, and self-field detachment.

We have performed a preliminary study of Hall effects on magnetic nozzle jets with weak guiding magnetic fields and weak expansions ($p_{jet} \approx p_{background}$). The conclusion from this study is that the Hall effect creates an azimuthal rotation of the plasma jet and, more generally, creates helical structures in the induced current, velocity field, and magnetic fields. We have studied plasma jet expansion to near vacuum without a guiding magnetic field, and are presently including a guiding magnetic field using a resistive MHD solver. This research is progressing toward the implementation of a full generalized Ohm's law solver.

In our paper, we will summarize the basic principle, as well as the literature survey and briefly review our previous results. Our most recent results at the time of submittal will also be included. Efforts are currently underway to construct an experiment at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL) to study magnetic nozzle physics for a RF-thruster. Our computational study will work directly with this experiment to validate the numerical model, in order to study magnetic nozzle physics and optimize magnetic nozzle design. Preliminary results from the PEPL experiment will also be presented.

Acknowledgments

This research is funded by a NASA Office of Chief Technologist Space Technology Research Fellowship.

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