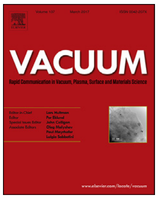
Vacuum 141 (2017) 22–31

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum



Investigating a two-stage electric space propulsion system: Simulation of plasma dynamics

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A R T I C L E I N F O

Article history:
Received 16 December 2016
Received in revised form
28 February 2017
Accepted 2 March 2017
Available online 7 March 2017

Keywords:
Space propulsion
Ion thruster
Hall thruster
Plasma simulation
Ion beam

A B S T R A C T

Electric propulsion presents an excellent alternative to conventional chemical counterparts as higher exhaust velocities from a plasma-based thruster allow for more efficient mass utilization and expanded space mission capabilities. Understanding the detailed time and space dependant physical phenomena within the main thruster could potentially enhance the capabilities of the electric thruster. Hence, in the present work a two-stage Hall thruster is investigated and the potential feasibility of coupling the two stages to produce the ion-beam is evaluated. The ionization and acceleration events are investigated via multiphysics simulations. The key trends ranging from the discharge inception, amplification and drift to formation of the ion beam are discussed and characterized.

1. Introduction

Electric propulsion (EP) uses a combination of electric and magnetic fields to accelerate propellant to extremely high exhaust speeds. The high exhaust velocity means that EP thrusters are able to generate large amounts of total impulse using relatively small amounts of fuel. This makes EP well suited to long duration, low thrust missions – for example, station-keeping of satellites and long term scientific missions [1].

Moreover, there is also an interest in lowering costs and enhancing the capabilities of space missions through the use of constellations of small satellites. EP is a well suited propulsion solution for this mission-type due to the small size, precise control, and high efficiency required on these satellites [2]. In addition, EP typically offers low-noise thrust, making it an attractive option for specific applications. For instance, in large scale interferometry experiments such as the Laser Interferometer Space Antenna (LISA) - where colloid thrusters have been tested to be used due to their low thrust noise and fine thrust control [3–5].

There are a variety of different EP thruster designs. Two of the most widely used and studied are the Direct Current (DC) ion thruster and the Hall thruster. Each type of these thruster designs offers different advantages. DC ion thrusters often have higher ionization efficiency and specific impulse, but suffer from life-limiting erosion due to their acceleration process at the grids. Additionally, the specific thrust of DC ion thrusters is space-charge limited and so often has lower specific thrust. Alternatively, Hall thrusters usually function at lower specific impulses, but are generally able to operate at greater thrust levels than ion thrusters. The ideal EP for a given mission is selected based on the specific impulse and thrust requirements for optimum efficiency, along with considerations of available power, size and lifetime [6].

The present work seeks to investigate a two-stage thruster in order to independently control ionization and acceleration processes. Previous work in the literature on a two-stage thruster have reported some inefficiencies present in high voltage operation of two-stage thrusters [7,8]. Though not strictly two stage, thrusters combining DC ion thrusters and Hall thrusters have been investigated for their wide range of efficient operation [9]. The present work will provide a model of a two-stage thruster and target the understanding of key parameters - using the methodology described in the next section.

2. Rationale of a two-stage thruster

A two-stage thruster allows for the ionization and acceleration processes of the propellant, Xenon in the present case, to be separated. The present work combines a DC ion thruster discharge

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http://dx.doi.org/10.1016/j.vacuum.2017.03.003

chamber with a Hall thruster acceleration. The Hall thruster acceleration process offers advantages over ion thruster grid-based acceleration. In particular, ion thrusters use a set of grid electrodes to accelerate ions and produce thrust [10,11]. This means that the extracted charge is purely positive, and is susceptible to ion beam saturation. On the other hand, a Hall thruster extracts the ion beam from a quasi-neutral plasma of ions and electrons. For this reason, the Hall thruster is not affected by space-charge limitations and a Hall style acceleration stage for acceleration allows for higher thrust density than a similarly powered ion thruster. Furthermore, grids are one of the primary sources of erosion in ion thrusters, and so removing them can potentially increase lifetimes [12]. Erosion does limit the lifetime of Hall thrusters as well, though effective magnetic shielding techniques are being developed [13].

There are several previous thruster designs which attempt to separate ionization and acceleration. The primary advantage expected from separating these processes is an increase in overall efficiency. An example of such a device is the SPT-MAG [14]. Dividing the ionization and acceleration into separate stages allows for each area to be more finely optimized for its specified purpose. Further potential advantages of a two-stage design are: reduced beam divergence, reduced erosion, and extended operating range [15]. Modeling of double stage Hall effect thrusters has shown that decoupling ionization and acceleration within the thruster may be difficult or infeasible [16–19]. It was found that, in models of the SPT-MAG, ionization efficiency was not very sensitive to the discharge voltage. This implied that significant ionization was occurring due to the acceleration voltage. The processes of ionization and acceleration need to be more fully decoupled in order to realize the expected advantages of a double stage system.

Another potential benefit of multi-staging may be that higher level acceleration potential can be used than regularly found in Hall thrusters [8]. Hall thrusters are limited in their voltage due to plasma instabilities which arise, reducing efficiency [20]. The higher electric potential of ion thrusters allow them to operate with higher specific impulses, and so greater propellant mass efficiencies. Conversely, Hall thrusters can generally produce more thrust at a lower specific impulse. These two traits mean that each type of thruster optimizes fuel usage for different mission types [6]. The two-stage thruster would ideally be able to operate at higher electric potentials while not being space-charge limited. Combining the advantages of each technology could allow the two-stage thruster to operate effectively in a wider range of missions – but there are challenges in understanding the core physical plasma behaviours.

3. Model

3.1. Governing equations: fluid model

For the present work, a fluid modeling formalism with a plasma component is used. It is interesting to note that particle methods, for example DSMC (Direct Simulation Monte Carlo) [11,26] have also been used for ion thruster and Hall thruster modeling and offer access to more precise localized parameters, however, fluid models can provide useful and complementary global physical information at a reduced computational cost. The plasma dynamics can be described by the first three moments of the Boltzmann equation. The drift-diffusion approximation allows for these moments to be reduced to conservation equations of electrons (Eqn (1)), and the electron energy density (Eqn. (3)). A multiphysics approach, combining the physics of the plasma, propellant, electric field, and magnetic field, was used in order to couple the different phenomena. In particular the plasma module within COMSOL was used to model the discharge using the equations given [27]. It should be highlighted that the formalism for solving plasma configurations has been validated (see for example [28,29]). The simulations incorporate coupling among species (electron, ion, excited species, and neutral particles) and fields (electric and magnetic fields). An axisymmetric configuration was used to model the hybrid thruster.

It should be noted that the axisymmetric configuration cannot account for three dimensional non-uniformities which might occur in some conditions but the two-dimensional treatment are deemed correct to capture core phenomena. The focus of the paper is to gain an understanding of the plasma dynamics within a hybrid thruster, consisting of an ionization section (ion thruster) and an acceleration section (Hall thruster). The influence of neutral gas, which can be important in some plasma cases [21–23], for instance on heat exchange close to walls has not been considered in the present simulations. The mesh used in the domain of the simulations consists of approximately 20,000 cells. It should be noted that the results have been tested with finer meshes in order to validate mesh independence.

$$\frac{\partial n_e}{\partial t} + \nabla\cdot\overrightarrow{\Gamma}_e = R_e \tag{1}$$

$$\overrightarrow{\Gamma_e} = -\left(\underline{\mu_e}\cdot\overrightarrow{E}\right)n_e - \underline{D_e}\cdot\nabla n_e \tag{2}$$

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla\cdot\overrightarrow{\Gamma}_\varepsilon = R_\varepsilon \tag{3}$$

$$\overrightarrow{\Gamma_\varepsilon} = -\left(\underline{\mu_\varepsilon}\cdot\overrightarrow{E}\right)n_\varepsilon - \underline{D_\varepsilon}\cdot\nabla n_\varepsilon \tag{4}$$

where n_e is the electron density, n_ε is the electron energy density, $\overrightarrow{\Gamma}_e$ is the electron flux, R_e is the electron rate expression denoting the number of electrons created or lost due to reactions per unit volume per second, μ_ε is the electron energy mobility, $\overrightarrow{E}$ is the electric field, $\underline{D_e}$ is the electron diffusivity (scalar or tensor depending on the form of μ_e), μ_e is the electron mobility, $\underline{D_\varepsilon}$ is the electron energy diffusivity, and R_ε is the electron energy source term. The electron diffusivity, $\underline{D_e}$, electron energy diffusivity, $\underline{D_\varepsilon}$, and electron energy mobility, μ_ε, are determined from Einstein's relation assuming a Maxwellian electron energy distribution in Eqns. (5-7). The Maxwellian electron energy distribution serves as a useful approximation for simulating plasma behaviour through the use of fluid and hybrid models. While this assumption may not be perfectly accurate, for electron-wall interactions, it serves as an effective method of determining global electron behaviour, as discussed in, for instance [24,25].

$$\underline{D_e} = \underline{\mu_e}\,T_e \tag{5}$$

$$\underline{D_\varepsilon} = \underline{\mu_\varepsilon}\,T_e \tag{6}$$

$$\mu_\varepsilon = \frac{5}{3}\mu_e \tag{7}$$

The electron temperature, T_e, is determined from the mean electron energy, $\tilde{\varepsilon}$ (Eqns. (9) and 8).

$$T_e = \frac{2}{3}\tilde{\varepsilon} \tag{8}$$

$$\tilde{\varepsilon} = \frac{n_\varepsilon}{n_e} \tag{9}$$

Electron motion is accounted for in the electron flux shown in