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The main goal of the work under this Grant was the clarification of the scaling properties of Hall thrusters, with a view to both, miniaturization, and expansion to high power. This goal was pursued through two complementary efforts, one addressing the scaling issues and technological problems associated with miniaturization of classically arranged Hall thrusters, and the other continuing the fundamental physical modeling work on Hall thrusters, which underlies all scaling work. In addition, work was also performed on the concept of improving arcjet efficiency through alkali seeding.

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Final Technical Report on Grant AFOSR 95-NA-253
"Basic Scaling Studies of Electric Thrusters"

by Manuel Martinez-Sanchez
March 12, 1999

1. Introduction

The main goal of the work under this Grant was the clarification of the scaling properties of Hall thrusters, with a view to both, miniaturization, and expansion to high power. This goal was pursued through two complementary efforts, one addressing the scaling issues and technological problems associated with miniaturization of classically arranged Hall thrusters, and the other continuing the fundamental physical modeling work on Hall thrusters, which underlies all scaling work. In addition, work was also performed on the concept of improving arcjet efficiency through alkali seeding.

In a recent Progress Report[1] , the work in the second year of the Grant was documented through four Conference Papers and two Master's Thesis. To avoid repetition, this Report will supplement the above with additional documents pertaining to our work prior to Aug. 1997 or subsequent to July 1998 (to Oct. 31, 1998). These documents will be summarized briefly in Sec. 2, and will also be attached as an Appendix.

2. Overview of Contributions

2.1 Miniaturized Hall Thrusters

Continuing on work initiated at MIT with funding from the Draper Laboratory (IRD, Draper FY 96), we have completed the design, fabrication and preliminary testing of a 50 W Hall thruster, using rigorous scaling arguments which should ensure the preservation of specific impulse and efficiency despite the size and power reductions. The scaling theory and the design of the thruster are detailed in Refs. [2], [3], which are attached to this Report. The salient conclusions of this work are:

-All relevant nondimensional ratios governing the operation of a Hall thruster can be made scale-invariant, with the exception of (Debye length/Length), which is deemed small enough to be irrelevant.
-If length is reduced by a factor L, so should power, current and flow rate. Magnetic field should be increased by 1/L, and voltage should be maintained constant. As a consequence, density increases as 1/L, and so does heat flux.
-The Ohmic power dissipated in a magnetic coil increases rapidly (as a fraction of total power) when size is reduced. Below some power (of the order of 100 W) permanent magnets become necessary. SaCo magnets suffice for powers down to 20-50 W, but no magnetic materials in existence can supply a strong enough field

below this size. An additional limitation occurs, at about the same power, due to saturation of the iron in the magnetic yoke.

-Cooling through conduction is favored by the size reduction, and the magnets can be kept cool enough through appropriate design to emphasize conduction to supports.

-Reductions in thruster life become inevitable due to the combination of higher heat and ion fluxes to walls, and reduced wall thicknesses. This unfavorable feature is not restricted to Hall thrusters, but will recur in any device where ionization occurs through electron impact in the gas phase (including, for example, ion engines and arcjets).

-Preliminary tests show the expected scaling as far as the voltage-current-flow characteristics is concerned. This is reported in papers included in Ref. [1]. Thrust stand testing was initiated at the Edwards AFB Laboratory, but uncertainties remain in the flow rate calibration, which prevent us from obtaining reliable performance figures as yet. Work will continue on this item.

2.2 Hall Thruster Modeling

Work has continued towards a reliable numerical model for the performance and detailed 2-D, time-dependent parameter distributions in Hall thrusters of the ceramic-lined type. This work was pioneered in our earlier publications (Fife, 1994-1995, Refs. [4], [5]). Additional parametric studies were reported in Ref. 6, and refinements on the treatment of wall interactions were introduced in Ref. 7, which also included a study of the calculated ionization oscillations in the thruster.

The principal results obtained can be summarized as follows:

-Electron cross-field diffusion is dominated in SPT thrusters by some anomalous (non-collisional) mechanism. The Bohm empirical diffusion formula, with slight adjustments, provides reasonable estimates, but substantial uncertainty remains in this area.

-The simulations identify a nearly in-situ ionization oscillation of large amplitude, in which phases of low and high ionization alternate, leading to the ejection from the thruster of nearly discrete "plasmoids". Simple modeling of these results yields equation which are formally identical to those of the predator-prey ecological models, and the ensuing cycles are analogous to the feast-famine ecological cycles. These oscillations are very similar in all their qualitative features to those long observed in SPT thrusters, most clearly in the visualization studies of Darnon et al [8].

-The efficient production of secondary electrons by ion-bombarded ceramic walls can have a profound effect on the structure of the wall sheath, the electron energy loss and subsequently, the electron temperature. Below some critical T_e (of the order of 16 eV for Boron Nitride) the wall emits less than one electron per arriving ion, and its current neutrality is maintained largely by the creation of an electron-repelling sheath potential which restricts the electon arrival rate to match that of the ions minus the few emitted electrons). But if T_e exceeds the critical, enough secondary electrons are emitted to render that sheath superfluous; the sheath collapses, the full random flux of electrons arrives at the wall, and the energy loss is drastically increased. This, in turn limits T_e to no more than the critical value at which the secondary yield reaches unity. These features are captured in the model of Ref. 7, and explain the observed $(T_e)_{MAX}$ in SPT thrusters. They also explain the higher Te seen in TAL thrusters, where the walls are metallic, and have low secondary emission throughout.

Work on these topics was later continued with a detailed experimental probe exploration of the near-plume of a SPT-70 thruster. This is discussed in papers reported in Ref. [1], and in more detail in J.M. Fife's Doctoral Thesis, which is appended here.

2.3 Seeded Arcjets

The work of Folusho Oyerokun and Darrel Robertson on this topic is fully discussed in Ref. [1], and will not be repeated here.

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4. J.M. Fife and M. Martinez-Sanchez, “Two-Dimensional Modeling of Hall Thrusters”. 3rd Russian-German Conference on Electric Propulsion, July 1994, Stuttgart, Germany.
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8. F. Darnon et al., “Dynamic Plasma and Plume Behavior of SPT Thrusters”, paper AIAA 98-3644, 34th Joint Propulsion Conf., July 1998, Cleveland, OH.

Appendix

Publications and Theses generated under this Grant (additional to those appended to Ref. (1))