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ABSTRACT
Estratto

This document represents the executive summary referring to the contract titled *Magnetic Nozzle For Plasma Propulsion Applications* between ESA and Centrospazio of Consorzio Pisa Ricerche.

KEY WORDS
Parole chiave Magnetic nozzle, Plasma, Electrons, Ions

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List of acronyms and abbreviations

Indice degli acronimi e abbreviazioni

AF	Applied Field
MPDT	Magneto-Plasma-Dynamic Thruster
HET	Hall Effect Thruster
MHD	Magnetohydrodynamic
PIC	Particle in cell
PICPlus	Particle in cell Plume Simulator
PIC-FES	Pic-Fluid Electron Simulation

1 Introduction

1.1 Purpose

This document represents the executive summary of the work performed by Centrospazio in the frame of the ESA contract 16756/02/NL/PA with title: *Magnetic Nozzle For Plasma Propulsion Applications.*

1.2 Scope

Scope of the document is:

- to describe the project objective;
- to summarise the performed work;
- to illustrate guidelines for future works.

2 Documents

2.1 Applicable Documents

AD	DOC. Code	Is.	Date	Titolo
AD 1	MPE/407/DN	2	07/10/02	Statement of Work, "Magnetic Nozzles For Plasma Propulsion Applications".
AD 2	CS/MNPPA/TN-01	1	15/10/03	"Assessment of the Theoretical Concept", MNPPA Technical Note 1.
AD 3	CS/MNPPA/TN-02	1	15/12/03	"Development of the Quantitative Model: the PIC-FES Code", MNPPA Technical Note 2.
AD 4	CS/MNPPA/TN-03	1	14/04/04	Development of the Quantitative Model: Electrons Fluid Dynamic Model", MNPPA Technical Note 3.

3 Introduction

The possibility of accelerating an hot plasma through a magnetic nozzle represents a very interesting alternative to the conventional gasdynamic acceleration through a real nozzle, since without the limitation on the gas temperature imposed by the material strength the engine performance, especially in terms of specific impulse, can be greatly improved. Moreover the magnetic nozzle effect can be advantageously exploited also in electric thrusters such as AF MPDTs and HETs.

With respect to this topic, the development of a numerical model for the simulation of plasma behavior in presence of a magnetic nozzle is of great importance since it automatically would represent also a powerful design tool for the new thruster, allowing to optimize thruster geometry, magnetic field topology and operating condition (for instance in terms of propellant) for the required performance.

The scope of the work of Centrospazio has been the development of such a model.

4 Outline of the performed work

The work carried out by Centrospazio has consisted of three phases.

In the first phase a deep review of main models, inclusive of their characteristics equations for plasma dynamics simulation and, in particular, for plasma expansion simulation inside a magnetic nozzle has been carried out. These models implement the following approaches or their combination:

- Particle model
- Numerical solution of equations of kinetic theory (Vlasov/Fokker-Planck)
- Two fluids model
- One fluid model (MHD)

Moreover, previous studies about plasma flow description inside a magnetic nozzle have been presented, in terms of their main hypotheses, most important results and limiting factors.

The models analysed are the following:

- Kosmhal's model: an analytical model based on the particle approach
- Sercel's model: an extension of the Kosmahl work
- Chubb's model: a theoretical model based on MHD equations.

Usually plasma simulation codes are based on the MHD model. A MHD type code, named MACH2, has been used for model different experiments on plasma and it has been useful to understand several physical phenomena. Unfortunately MHD model bases on a series of restrictive hypotheses, especially when the Hall physical effects are not negligible. That is the case of MPDTs, in which the Hall parameter is variable between 3 and 5.

In this view an alternative approach it was followed in order to investigate plasma behaviour inside an AF MPDT. This was the object of the second and third phase of the work.

The plasma modelling using the kinetic theory represented an alternative way. This approach follows the Boltzmann equation with the collision term given by its collision integral or by the Fokker-Planck collision term. This scheme requires to solve the Boltzmann equation for each species in the plasma, and involves the use of seven dimensional variables (three for velocity, three for space and one for the time). Therefore this scheme can be used in limited applications. Moreover the boundary conditions are difficult to define for a simulation with a kinetic approach.

Another possibility was investigated for utilising either a two fluids scheme or a particle one. The study of plasma dynamic with particle code (PIC), has demonstrated to achieve better results than two fluids, MHD and kinetic code. In fact, the PIC schemes allow to model complex configurations without introducing hypotheses a priori. As they are very "computational expensive", it is preferable to adopt a Hybrid-PIC code using the particle model for the ions dynamic and a fluid-dynamic model for electrons one. In fact, the electrons, for their high mobility, are submitted to a larger number of collisions than the ions and thus can be analysed more efficiently by continuous model. Another advantage of this model is the possibility to use time steps higher for the electrons; in fact the electrons have velocities higher than ions (they require time steps too small for the simulation). At the end this last alternative has been chosen.

The second phase of the work concerned in the development of the particle model for ions. At this purpose the PICPlus code, developed by Centrospazio in order to simulate the plume of the SPT-100 Hall thrusters, has been adapted. The PICPlus code is a powerful tool that allows to predict the interaction between the plume and spacecraft surfaces. The characteristics of the jet are defined by the combined effects of the charge particles and magnetic field. The PICPlus code allows to predict the evolution of the plasma exit from the thruster, but it doesn't consider the internal phenomena. Therefore it was necessary to modify the code to simulate the plasma injected from the hollow cathode of the AFMPDT and physical phenomena as the interaction of plasma with the electric field generated by electrodes, and the interaction with the insulated solid walls. The main modifications are:

- Development of a new routine to generate the computational grid.
- Modification to use one only ionic species.
- Modification of routine for the ions injection.
- Development of new routines to calculate the magnetic fields.
- Modifications of boundary conditions on the potential.
- Modification of tools to calculate potential and electric field
- Development of new routines to model the electrodes and the dielectric walls.
- Development of new routines to describe the electrons dynamic.
- Removal of the routine for the collisions treatment.

The PIC code for ions with a simplified electron model was used to extensively test magnetic nozzle influence on a realistic Hybrid Plasma Thruster performance. It demonstrated the possibility to obtain significant thrust increase without other disadvantages. The results are also consistent with the ones found in literature.

In the third part of the work, the electrons fluid model has been elaborated. Every single species in the plasma was described by equations, expressing the mass, momentum and energy conservation; they result similar, in the shape, to Navier-Stokes's equations except for some terms that specify the interactions between the species.
To reduce the complexity problem some simplifications have been introduced:

- One ionic specie (Ar^+) in the plasma;
- Neutral atoms are neglected;
- Gravitational acceleration is neglected;
- No viscosity ($\overline{\overline{p}}_e = n_e k T_e \overline{\overline{I}}$);
- Only electron-ion collisions are considered;
- Heat fluxes are negligible

Subsequently the numerical procedures for the electrons model have been tested in a simplified configuration without ions, achieving good results.

Finally, after having verified the ions and electrons code, the complete PIC-FES code (particle approach for ions and fluid-dynamic approach for electrons) has been run to perform a simulation of an AF MPDT, and the achieved preliminary results have been reported.

5 Conclusions

A new numerical code has been developed for the simulation of plasma behavior in an AF MPDT and, more in general, in any device implementing a magnetic nozzle effect.
The PIC-FES code developed, belongs to Hybrid-PIC 2D-3V methods category. The behaviour of the positive ions in the plasma, which defines the performance of the thruster, is described by a particle approach, while the electrons motion by a fluid-dynamic one. Even if the problem geometry is considered axial-symmetric and bi-dimensional (2D), all velocity components, and thus the momentums of particles have to be maintained (3V). This aspect is useful to model the collisions between the particles and, in particular, the tangential currents which interact with the applied magnetic field and generate the electro-magnetic forces, $j_\vartheta B_z$, that confine plasma radially.
The complete code, tested on simplified configurations, requires some more work in order to reach a major level of maturity. However this new code represents a significant progress towards the development of complete simulation tools for this kind of thrusters and, at the same time, for the understanding of basic effects like the use of magnetic nozzles on realistic configurations.