MPD Thruster Plume Diagnostics

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Plasma diagnostics with Langmuir and magnetic probes allow important information to be gathered on MPD thruster behaviour, despite their relative semplicity and low cost. Diagnostic activities with these kind of devices have been carried out at CENTROSPAZIO to better characterize the operation of the thrusters developed both with and without cathode heating. A series of measurements to evaluate electron temperature and density, plasma potential and magnetic field at several points in the plume and around the electrodes at 2 g/s of Argon were performed on a cold cathode thruster with the same configuration as the thruster with cathode heating. An estimation of the electron Hall parameter near the electrodes was made on the basis of measured number density and magnetic field. Values exceeding the unity were found both at the anode and cathode regions. Some information on current distribution at the electrodes and power deposition in the plasma was also obtained. In particular, it was noted that the energy deposition near the electrodes (expecially the cathode) is percentually very marked at low values of current, while at higher current values the energy seems, for the most part, to be dissipated in different plasma regions.

Nomenclature

A_p = probe collecting surface, m^2
b = electromagnetic thrust coefficient,N/A^2
B = magnetic field, T
B_θ = azimuthal component of magnetic field, T
ΔV = voltage fall, V
e = electron charge, 1.6 x 10^{-19} C
E = electric field, V/m
ε_0 = permittivity of free space, 8.85 x 10^{-12} F/m
η_t = thrust efficency
I = current , A
I_1 = current saturation probe 1, A
I_2 = current saturation probe 2, A
I_{sp} = specific impulse, s
I_{fi} = full ionization current, A
j = current density, A/m^2
k = Boltzmann's constant, 1.38 10^{-23} J/K
m_e = electron mass, 9.11x 10^{-31} kg
m = mass flow rate, kg/s
M_i = Argon ion mass, 6.63 x 10^{-26} kg
n_e = electron number density, m^{-3}
n_i = ion number density, m^{-3}
ν_{ee} = electron-electron collision frequency, s^{-1}
T_e = electron temperature, K
λ_D = Debye length, m
V = voltage, V
ω_e = electron ciclotron frequency, rad/s.
Ω = Hall parameter

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Introduction

Simplicity in design and the possibility to obtain high specific impulse together with high thrust density, using a wide range of common and easily storable propellants, may be considered as the most actractive characteristics of MPD thrusters. Nevertheless, some mission and system studies have shown that these devices could yield advantages, as primary (continuous) or auxialiary (pulsed) propulsion systems, only if a thrust efficiency beyond 50% and a low electrode erosion rate are achieved [1,2,3]. As a consequence, a great deal of efforts has been made to solve these critical problems through experimental and theoretical activities, carried out in several laboratories in the world. These studies have shown that MPD thrusters provide a better performance when operating at higher power levels as opposed to lower ones [4]. Power availability in space for the medium and long term and the present state of the art, have practically fixed the typical MPD power range at few MWs, even if studies on multi-GW devices have been carried out [5]. At MW power levels, it is possible to accelerate the propellant significantly by means of electromagnetic processes, obtaining thrusts in the order of tens of Newton. Experimental results have shown that the Lorentz acceleration is the largely predominant mechanism that contributes to the thrust on multi-MW thrusters, in the partial as well as in the full ionization regime [6,7]. An increase in thrust, and thus an increase in thrust efficiency, using plasma thermalization, is currently achieved especially on applied-field MPD devices [8,9]. Nevertheless, the principle to significantly improve thrust efficiency in MPD thrusters, is to reduce the dissipative phenomena, rather than to increase the thrust [7]. Moreover, the reduction of these detrimental processes will also reduce the erosion of the thruster components, thus prolonging the thruster life.

Electrical characteristic and thrust measurements allow thruster performance to be calculated in terms of specific impulse and thrust efficiency. However, the measurement of these external quantities can only give at the most qualitative information on plasma quantities, and no indication on power allocation in the plume and on the electrodes. Important information on plasma quantities and thus on dissipation rates can be obtained through plume diagnostics.

In the framework of a recently concluded ESA programme, carried out at CENTROSPAZIO, experimental results gathered on a family of quasi steady, gas-fed MPD thrusters have highlighted some geometry and scale effects on thruster performance [10,11]. Moreover, a thruster with an artificially heated cathode, simulating the thermal condition of a continuous operation, was developed and tested [12]. The measurement of electrical characteristics and thrust provided a considerable amount of information, which agreed well with results obtained on analogous thrusters in other laboratories. In particular, the advantage of gas injection towards the anode and general improvements in performance with cathode heating were highlighted. Experimental activities on the thruster with cathode heating will be pursued in order to gather additional experimental results to confirm those already available [13]. Plume diagnostic activities will also be carried out on this thruster to investigate cathode heating effects.

A series of measurements with electrostatic (Langmuir) and magnetic probes (B probes) were carried out in the plume of a cold electrode thruster, with approximately the same geometry as the thruster with cathode heating. These tests were mainly focused at investigating the plasma regions near the anode and the cathode. An objective of testing was to set the diagnostic devices and the test procedure in order to perform the tests on the heated-cathode thruster effectively. The most significant results gathered to date are illustrated in the following.

Experimental Apparatus

The test activity was carried out on a ring anode MPD thruster, in the configuration classified as 1B5CAC (Fig. 1). This configuration belongs to a family of thruster developed in the framework of a previous activity and is the most similar to the one adopted for the thruster with cathode heating available at CENTROSPAZIO [11,12]. The thruster has an anode-to-cathode radius ratio of 5; the anode has an inner diameter of 100 mm and is made of deoxided copper. It has a larger and deeper surface exposed to the current, with a broad, elliptical profile connecting the internal and the external lips. The cathode is 20 mm in diameter, made of 2% thoriated tungsten and completely enclosed within the discharge chamber. The gas used during testing was Argon and it was exclusively injected at the cathode root. The hemispherical discharge chamber is made of Boron Nitride, while the other insulators are made of PVC.

Test Equipment

The thruster is mounted on a flange placed on the port of a fibre-glass vacuum chamber 0.8 m in diameter and 1 m in length, with a diffusion pump capable of a pressure level during tests of about 4.10^{-5} mbar prior to each discharge.

A commercial solenoid valve was used to produce a gas pulse of about 60 ms in duration associated with each discharge. The electrical power is supplied by a Pulse Forming Network of 12,000 μF capacitance, capable of a maximum discharge current of 30 kA with a pulse duration of about 1 ms.

The discharge is activated by an electronically-controlled Ignitron switch so as to cause the breakdown with a predetermined delay after the operation of the valve, when the mass flow rate has reached a steady value [10].

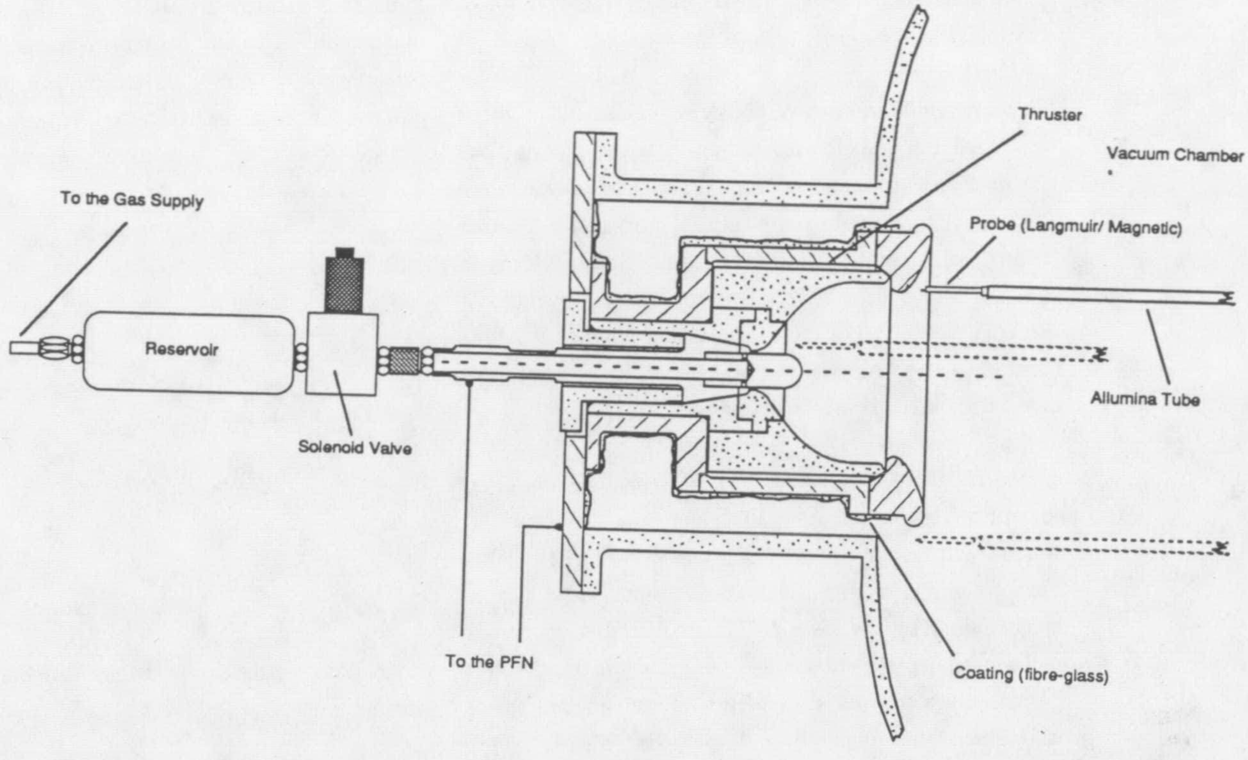

Fig. 1 Experimental Apparatus

The electrostatic and magnetic probes are placed inside the vacuum chamber with a probe positioning system, that provides three degrees of freedom in accordance with a cylindrical reference system [14]. The system enables probes placed in the centre of the wheel to cover a cylinder of 300 mm in diameter and 480 mm in length, with a repeatability error of less than +/- 0.5 mm. Nevertheless, a probe position check was carried out before each test for measurements carried out in proximity to the thruster electrodes. The movement of the system is assured by three step motors, one for each degree of freedom.

Two high voltage probes (Tek 6015-1000X) and an operational amplifier (Tek AM501) were adopted for voltage drop measurement between the thruster electrodes or plasma potential with respect to a reference electrode, as specified in the following. A Rogoswski coil with a passive integrator was adopted for total thruster current measurement [11].

Langmuir Probes. Asymmetrical double Langmuir probes were adopted to measure electron temperature and ion number density. The probe size was select by considering the typical characteristics of an MPD thruster plasma. The tungsten filaments were 0.2 and 0.05 mm in diameter each and 2.5 mm in length; the electrodes were spaced at 2 mm from each other. The electrodes were inserted on a alumina stick and welded to a twisted and shielded cable. In order to obtain Langmuir probe electrical characteristics, the electrodes were floating with respect to the plasma and were supplied by a current amplifier driven by a function generator (HP 8116A) [14]. The amplifier supplies a triangular wave (with a range of 5 - 20 kHz in frequency) with an amplitudeof +/- 12 V during the discharge. The voltage was measured directly at the current amplifier, while the probe current was measured by a Tek P6021 current probe. The signals were gathered on a transient recorder (HP 5185T), set to keep the traces at 0.5 ms in the discharge. The traces were transferred to an HP 9330 CMA for digital filtering, analysis and storage. The electron temperature was calculated from the Langmuir probe electrical characteristics, assuming a Maxwellian electronic distribution, in accordance to the following relationship [15]:

$$k\,T_e/e = \left[\frac{dI}{dV}\right]_{I=0} \frac{I_1 I_2}{I_1 + I_2}$$

and thus the ion number density, in accordance to the Bohm's approximation [15]:

$$n_i = 2\,I / \left(e\,A_p \left(k T_e / M\right)^{0.5}\right)$$

These assumptions imply the Debey length (λd) to be much shorter than the electrode radius and the probe surface to approximate the effective collection surface[16]. These conditions are usually verified in the plasma considered.

Plasma potential measurement. The same electrostatic probes were used for voltage measurements in the plasma. The voltage drop with respect to a thruster electrode was measured by connecting the two high voltage probes to a floating electrode of the probe and to the reference thruster electrode and connecting the high voltage probes to the operational amplifier AM 501. The value measured in this way was then corrected with a term proportional to the electron temperature in order to obtain the plasma potential [15,17].

Magnetic Probes. Magnetic field measurements were carried out with a B probe, consisting of an alumina core surrounded by a coil with 25 turnings of 0.1 mm copper wire. The coil was fixed on an alumina stick and was protected from plasma contamination by a glass cap. The coil was then connected with a low inductance coaxial cable to an integrator-amplifier. The entire system was calibrated with an Helmholtz Coil designed and manufactured for the purpose[18]. Measurements were gathered on the transient recorder and then transferred to a computer (Macintosh IIvx) for data analysis and storage.

Experimental Results

Tests were carried out on the thruster at 2 g/s of Argon and a current ranging from 4500 to 13000 A. All of the experimental results were taken at 0.5 ms of the current pulse. Each data point is an average of three or four measurements carried out at the same PFN charging voltage. In order to verify the reliability of the electrostatic and magnetic probes, a preliminary series of about twenty firings were carried out on each of them, keeping the probes at the same position (far from the electrodes) and charging the PFN at the same voltage. A repeatibility error of less than 5% for electron temperature and magnetic field was exhibited and the probes were considered reliable.

External quantity measurements. The electrical characteristic (Fig. 2) measured has the shape typical to observed on other MPD thrusters with gas injection at the cathode root: a linear dependence of the voltage from current in the first part, a steeper dependence after reaching a critical condition (at about 8000 - 8500 A in this case) followed by an asyptotic behaviour, indicating a strong erosion of the thruster components. Assuming a pure electromagnetic thrust and an electromagnetic thrust coefficient $b = 2.34\ 10^{-7}$ N/A^2, in accordance with thrust measurements carried out on a similar thruster [11], the performance, in terms of specific impulse (I_{sp}) and thrust efficiency (η_t), can be evaluated, as follows:

$$I_{sp} = \frac{T}{mg}$$

and

$$\eta_t = \frac{T^2}{2mVI}$$

having assumed [11]:

$$T = bII_{fi} \quad \text{for } I \leq I_{fi}$$

and

$$T = bI^2 \quad \text{for } I > I_{fi}$$

The thruster performance at 2g/s derived accordingly are shown in Fig. 3.

Mapping plasma quantities. Plasma diagnostics were mainly aimed at investigating the electrode regions in the electromagnetic regime of the thruster. The measurements were therefore performed close to the full ionization condition, ranging from about 7500 to 9800 A. Within this current range, plasma quantities were measured on points at 3 and 5 mm from electrode surfaces and on the anode exit plane.

Each electron temperature and ion number density data were obtained as an average of three probe electrical characteristics gathered at the same PFN charging voltage. Particularily noisy signals, almost gathered near the anode, were not considered. Other signals were considered after a non-recursive low-pass digital filtering [19]. Considering the critical position, the electron temperature precision near the electrodes is about 20% and about 15% for measurement on the anode exit plane at more than 10 mm from the electrodes. The number density precision does not exceed 50%, due to the incertainty involved in determining the real collection area, and also the probe contamination from the tungsten sputtered by the cathode during the thruster operation, a phenomenon observed during testing.

Mapping along the anode exit plane has shown there is no significant asymmetry in temperature and density distribution in the plume. The electron temperature measured ranges from 2.5 to 3.5 eV and does not seem to significantely vary with the position (higher values near the electrodes, and the cathode in particular) within the current range considered. Fig. 4 shows

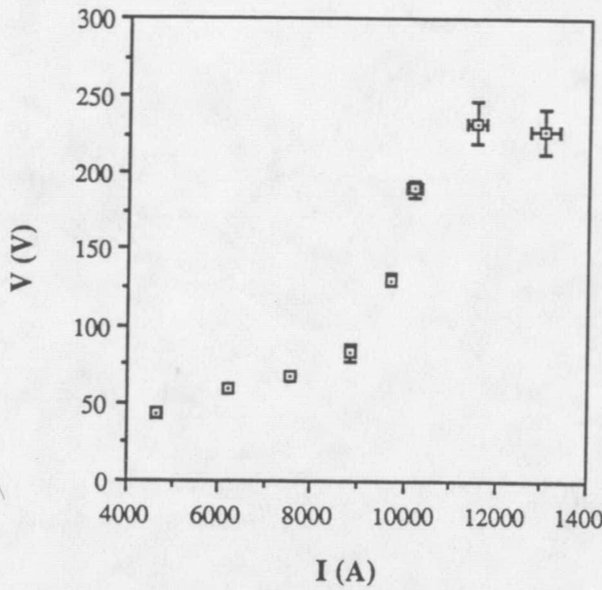

Fig. 2 Thruster electrical characteristic at 2 g/s of Argon

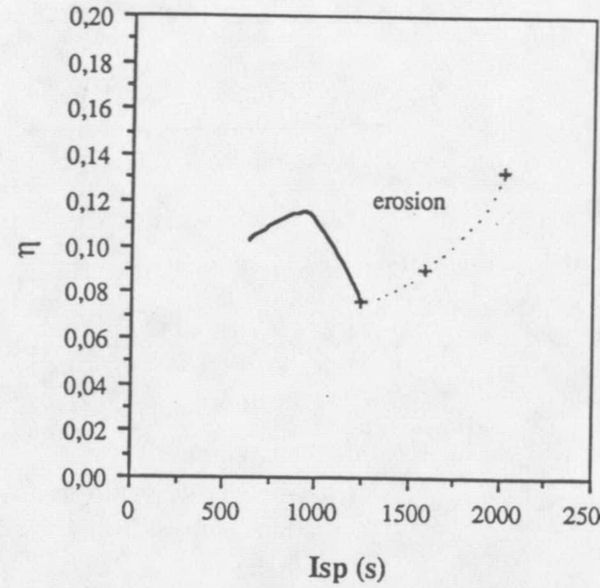

Fig. 3 Thrust efficiency vs. specific impulse

electron temperatures at 8800 A.

On the contrary, the number density has a strong variation, passing from cathode to anode region. Values in the order of 10^{21} - 10^{22} m^{-3} were found near the cathode, while values of 10^{19} - 10^{20} m^{-3} are typical in the anode region. A significant increase in ion number density with the current was observed in the cathode tip region, that can probably be justified by an increase in ionization rate and in the Lorentz blowing component with the current [20]. On the other hand, the number density does not vary significantly near the anode. Fig. 5 shows ion number densities at 8800 A.

The B probe was used to measure the azimuthal component of the magnetic field. At current levels close to the full ionization condition, the signals gathered present the typical fluctuation also observed in the voltage drop signals, due to electromagnetic noise [21]. Anomalous and quite random signals were gathered, especially near the cathode, at high current levels. These anomalies could be attributed to high frequency perturbations gathered by the B-probe and not properly integrated [22,23]. These doubtful signals were rejected. Further investigations and improvements of the measuring device, aimed at solving these problems will be performed in further diagnostic activities.

Asymmetries in B measurements were osberved, when moving the probe along a thruster diameter. This anomaly, also observed in other laboratories on similar devices, is generally due to asymmetry in the current discharge [24]. A significant magnetic field was also measured outside the discharge chamber (Fig. 7) in the entire current range. This occurrence indicates the extension of the current lines outside the thruster and current attachment on the outer anode surface, in low density region, as described in the following.

Electrode current distribution. Current distribution in the plume and on the electrodes can be evaluated from magnetic field measurement, by applying the Ampere's law. The cathode and anode current distribution illustrated in Figs. 8, 9, 10 for three current levels was estimated on the basis of the azimuthal magnetic field measurements. For this purpose, the enclosed current flowing through a coaxial, circular region was assumed to be proportional to the azimuthal magnetic field measured on the limiting circumference and to the circumference radius. This simple approach implies an azimuthal symmetry of the magnetic field, that tests have shown as not always true. As a consequence, the electrode current distribution illustrated should be considered indicative of qualitative behaviour. The percentage was calculated with respect to the total current measured externally with the Rogoswski coil. The percentages in brackets indicate that quantity was not measured but was simply obtained as a remaining fraction to reach the unity. From Figs.8, 9, 10, the following observation can be made:

- *anode region*. The power level seems to influence the current distribution on the anode surface substantially. At 7500 A, the current is concentrated on the internal lip, almost on the inner anode surface (about 65%). The large external surface gathers

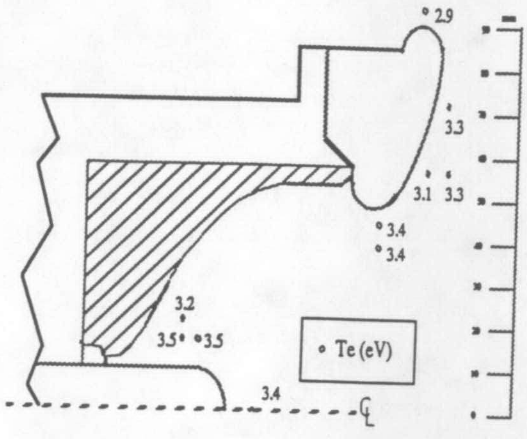

Fig. 4 Electron temperature mapping (8800 A)

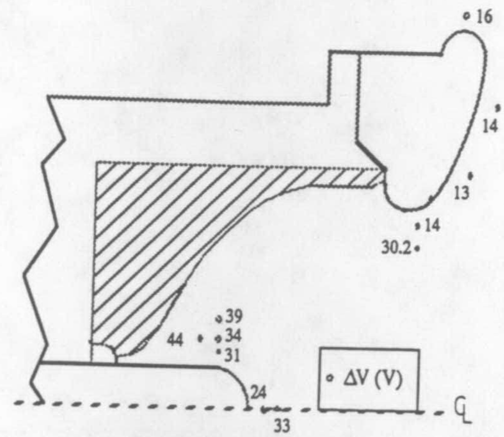

Fig. 6 Plasma potential mapping (8800 A)

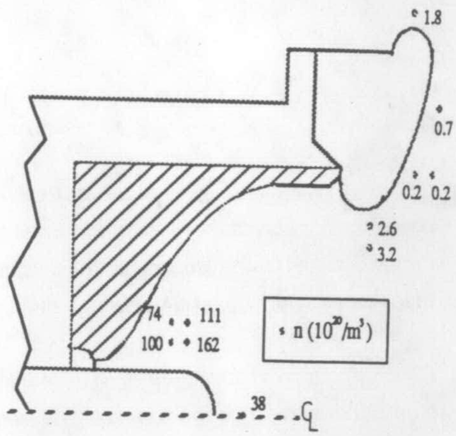

Fig. 5 Ion number density mapping (8800 A)

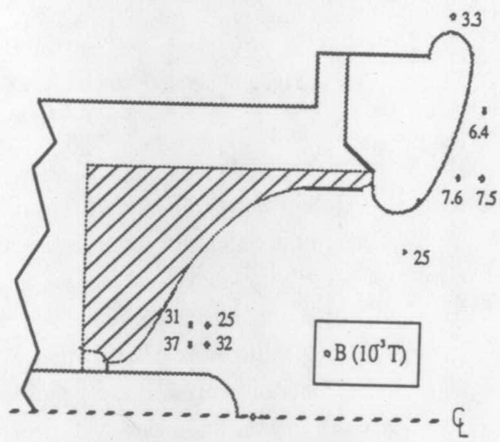

Fig. 7 Magnetic field mapping (8800 A)

less than 30% of the total current, while a significant percentage (about 9%) is gathered by the external lip and by the uncoated outer-anode surface. This percentage increases when the current level is increased (until about 26% at 9800 A). The current tends to concentrate towards the external anode surface, while the inner surface gathers less and less current (from 65% at 7500 A to about 38% at 9800 A). On the contrary, current density on the intermediate surface seem substantially unaffected. The current concentration on the anode lips is roughly confirmed by observation of the anode surface, after testing. Char traces are in fact localized in these regions in particular.

- *cathode region.* The current distribution is available only for 7500 and 8800 A, while results for 9800 A were not considered, as they were particularily anomalous and doubtful, as specified above. For the conditions considered, the current distribution does not seem to be substantially influenced by the power level. The cathode tip, with about 1/3 of the nominal cathode surface, has the highest current density (more than 1.5 of the average current density), gathering about half of the entire current. This concentration on the cathode tip justifies the strong erosion observed in this area after testing. The intermediate surface seems to exhibit a lower current density (about 0.6 the average density), while a high current concentration at the cathode root is possible, with 40% of the current located on the back cathode surface (current density 0.8 of the average density). This confirmed what was already suspected due to the carbon residue observed on the insulator near the cathode after testing. A more detailed current distribution could be obtained by measuring the magnetic field closer to the cathode root [25]. Unfortunately, this measurement would be quite difficult to make, due to the discharge chamber configuration adopted.

Power deposition near the electrodes. Knowledge of current distribution and plasma potential permits to evaluate the electrical power distribution within the arc and the identification of regions where a significant amount of power is allocated [25].

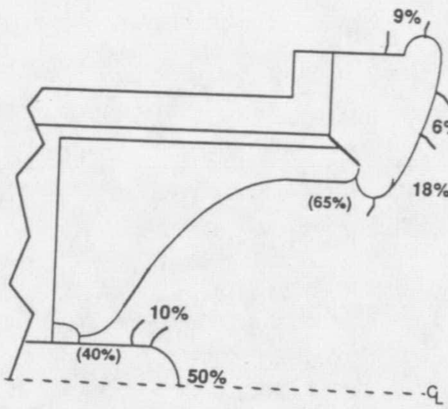

Fig. 8 Electrode current distribution at 7500 A

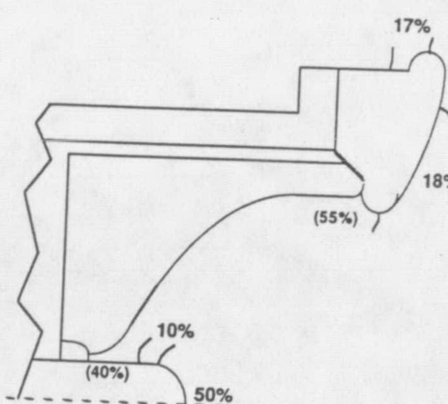

Fig. 9 Electrode current distribution at 8800 A

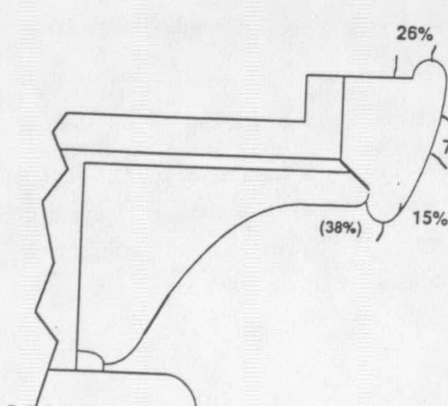

Fig. 10 Electrode current distribution at 9500 A

Plasma potential was measured near the electrodes and in the discharge chamber, by means of floating electrostatic probe, as described above. The potentials near the electrodes were referred to the relevant electrode potential. The following observations can be made:

-*anode region*. It is well known that the anode region is one of the most critical, due to the large amount of power there dissipated. For this reason, the need for a higher thrust efficiency implies a substantial reduction of power deposition on the anode. Extensive studies, carried out both recently and in the past, have been focused at investigating anode phenomena and power deposition and a considerable amount of data are already available in the literature [26-30]. In particular, the anode fall voltage has been demonstrated to be the most significant cause of power deposition on the anode, and seems to be the quantity that is more substantially affected by controllable factors, such as mass flow rate distribution, applied magnetic field, anode shape, etc. In Fig. 11 the anode fall voltage measured on four points at 3 mm from the anode surface was compared with the arc voltage drop. For current levels of up to 8800 A (that is, practically, the full ionization current), the line contouring the anode surface at a distance of 3 mm seems to be an equipotential line and the anode voltage loss does not vary significantly, being about 15 V at 4500 A and 18 - 20 V at 8800 A. As soon as this current level is exceeded, the voltage loss increases sharply, roughly following the same pattern of the electrical characteristic; the 3 mm line is not an equipotential line but, inside that layer, the equipotential lines seem to accumulate from the inner to the outer surface. An asymptotic behaviour seems to be reached for the same current range for which an analogous behavior can be observed on the electrical characteristic (erosion regime).

-*cathode region*. The cathode fall voltage was measured on a few points 5 mm from the cathode surface, as illustrated in Fig. 12. The values measured show no significant variation with the current level, ranging from 30 to 40 V [25]. The cathode fall voltage seems scarcely to increase up to about 9500 A, and then decrease in the erosion region.

In Fig. 13 the anode and cathode fall voltages, weighted on the basis of current distribution estimation, are represented in percentages with respect to the arc voltage drop as a function of the current, together with the estimated thrust efficiency. At low power levels, the energy seems to be predominantly deposited in the cathode region. In this current range, the dissipative phenomena seem to be allocated in the electrode region in particular. When the current level is increased, the percentage of energy decreases around the cathode, while it increases within the anode region. A general decrease of

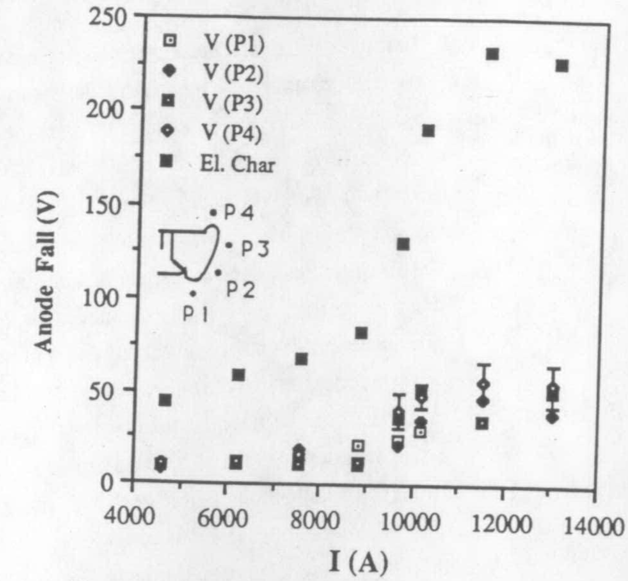

Fig. 11 Anode fall and arc voltage comparison

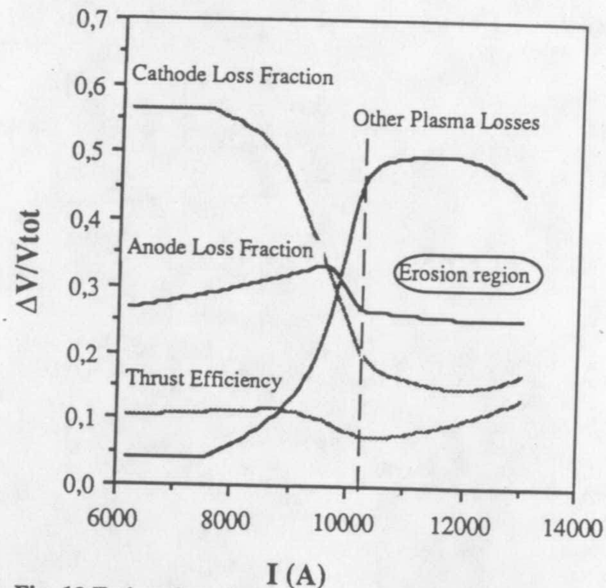

Fig. 13 Estimation of energy distribution in the plasma

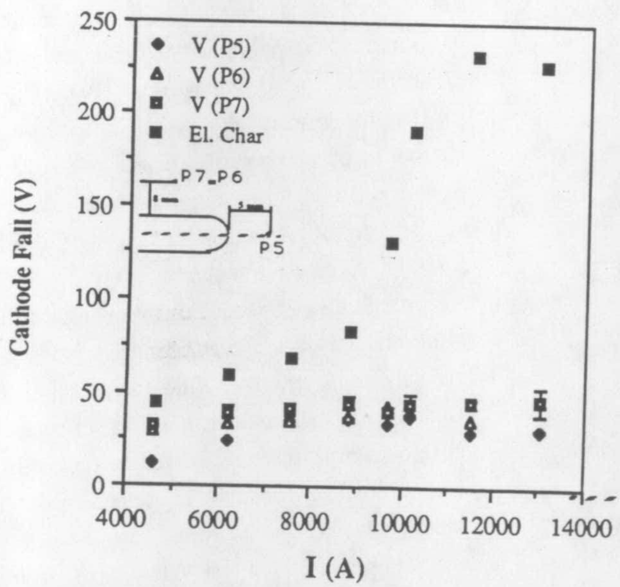

Fig. 12 Cathode fall and arc voltage comparison

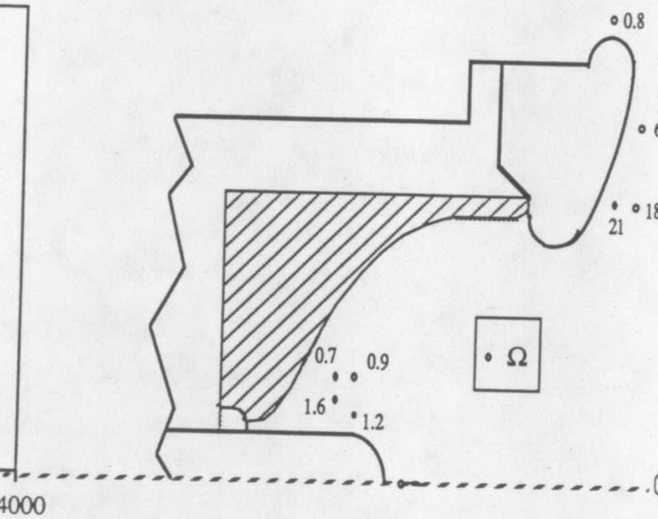

Fig. 14 Electron Hall parameter distribution at 8800 A

efficiency, energy percentage in the cathode and in the anode region can be observed after reaching the full ionization condition. Considering roughly the voltage percentage, a significant power dissipation has to be allocated in not investigated plasma region, different from the electrode layers [3]. In the erosion zone, the electrode energy deposition, as a percentage, seems to reach an asymptote. The increase in thrust efficiency depends on the eroded mass contribution, and is thus overestimated.

Electron Hall parameter estimation. The number density and magnetic field measurements allow the electron Hall parameter to be estimated [16]. This parameter indicates the degree of isotropy of the current flow and seems to be strongly correlated to the anomalous resistivity, due to turbulence in the plasma [29]. The electron Hall parameter was calculated according to the following expression [16]:

$$\Omega_e = \frac{\omega_e}{\nu_{ee}}$$

where:

$$\omega_e = e\frac{B}{m_e}$$

and

$$\nu_{ee}=\frac{n\pi e^4}{m_e^2 (k T_e/m_e)^{3/2}}$$

As shown in Fig. 14, high values were found near the anode (from 1 to 20), and values around the unity are also obtained near the cathode [25]. This occurrence shows the criticity of the anode region as regards anomalous transport phenomena [29] and the consequence of diffusion effects with respect to isotropic effects (such as collisions) in the cathode region. More detailed observations can be made when more data are made available.

Conclusion

Plasma diagnostic activities on MPD thrusters with electrostatic and magnetic probes are underway at CENTROSPAZIO. One of the most important objectives of these activities is the identification of the energy deposition in different plasma regions and possibly of the physical reasons of that power allocation, obtained by measuring the local plasma parameters. This information represents a fundamental contribution to facilitate thruster design and to more fully understand performance changes that can be obtained, for instance, by varying the gas injection mode, the thermal condition of the electrodes or their geometrical configuration. Preliminary results from plasma diagnostics have been obtained on a cold electrode thruster, operating with the gas injection at the cathode root, having the same configuration of the thruster with cathode heating. On the basis of these results, the following conclusions can be drawn:

- for the entire current range investigated, a great amount of power is deposited near the electrodes; as a percentage, the electrode losses are considerably greater at low currents (partial ionization regime) than at higher currents (full ionization regime).
- soon after the full ionization condition, the decrease in electrode power fractions corresponds to the decrease in thrust efficiency, thus indicating that a percentually high fraction of power is deposited in plasma regions yet to be investigated. This occurrence seems to confirm the existence of plasma zones not directly close to the electrodes where power is dissipated in plasma instabilty and turbulence not recovered in thrust.
- in the full ionization region, electron Hall parameter values exceeding the unity were found not only in the anode region, but also near the cathode, indicating a remarkable interaction between current and plasma flow in that region [25].

Acknowledgements

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