PERFORMANCE OF AN APPLIED FIELD MPD THRUSTER WITH A PRE-IONIZATION CHAMBER

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ABSTRACT

The paper deals with an experimental activity carried out on an applied field MPD thruster with a pre-ionisation chamber, called HPT (hybrid plasma thruster). The HPT has been jointly developed by RIAME-MAI and Centrospazio, starting from a design proposed by Prof. Tikhonov. The HPT consists of two stages (chambers) divided by a half-transparent anode. The first stage serves for the preliminary ionisation of part of the propellant by means of a secondary discharge between peripheral cathodes and the anode itself and the second one is used for ionisation and acceleration of the total plasma flow. The results illustrated was obtained using argon as propellant at a mass flow rate of 220 mg/s, injected in different proportion from the central and the peripheral cathodes, with an applied field up to 100 mT on the axis and an arc power from 100 to 400 kW. Results indicate the injection mode can significantly affect the performance of the HPT, also without the activation of the secondary discharge. The total mass flow rate the same, the performance increase by increasing the percentage of mass flow injected by the peripheral injectors, especially at low power. The activation of the pre-ionisation chamber has given contradicting results. The improvements observed during a campaign indicate the substantial effectiveness of the concept, but the current HPT configuration has proven to be not reliable enough for a thorough assessment of the thruster operation, since the same improvements were not observed in a subsequent campaign. An improved HPT with independent peripheral cathodes will be tested in the following months.

INTRODUCTION

Applied field magneto-plasma-dynamic (AF-MPD) thrusters are a promising technology for high specific impulse, high thrust missions requiring a significant delta-V. AF-MPD thrusters are often referred to as an optimal solution for a large payload mission to Mars, such as a manned mission precursor[1, 2]. As opposed to classic self-field MPD thrusters, AF-MPD thrusters retain a satisfactory performance even when scaled down to the 100-500 kW power range which seems appropriate for medium term missions.

The recognized main features of AF-MPD thrusters are the high specific impulse (1000 to 5000 s), high thrust density (as high as 10^5 N/m^2), robustness (no grids, no moving parts) and capability, in principle, of using a large variety of propellants: alkali metals (lithium), gases (helium, argon, krypton, xenon, hydrogen, nitrogen, ammonia, hydrazine, gas mixtures) polymers (Teflon) in-situ produced (extraterrestrial) propellants, etc. These features are mostly shared with the self-field MPD thrusters, whose optimal power range is however yet higher (MWs). In self-field MPD thrusters, the main acceleration mechanism is represented by the interaction between the discharge current and the self-induced magnetic field (self-magnetic Lorentz acceleration): as a consequence, high thrust level can be obtained for high discharge currents (5-100 kA) and, consequently, for high powers. On the contrary, the application of an applied magnetic field introduces new acceleration mechanisms (mainly gasdynamic and Hall effect) that do not directly depend on the discharge current and thus can allow the thruster to effectively operate at lower powers [3-5].

However, although many efforts have been spent so far in research on MPD propulsion and promising results have been also obtained, important issues remain to be assessed, in particular:

- the achievement of acceptable performance, especially in terms of thrust efficiency (mission studies indicate 50% at least);
- the development of long-life cathodes, compatible with the envisaged operation time for primary missions, (5000-10000 hours).

The achievement of acceptable performance is generally hampered by the occurrence of detrimental phenomena, usually referred as "onset phenomena", taking place when a critical current is exceeded, depending on thruster geometry, propellant and mass flow rate. Onset phenomena involve arc voltage fluctuations, power losses and, eventually, strong erosion or melting of thruster components (anode in particular). Several studies indicate the near-anode zone is the most involved region in onset phenomena [6, 7]. This last occurrence is attributed to the joint action of pinch and Hall effect, which tends to compress the plasma to the thruster axis and, consequently, to reduce plasma density in the anode region. The relevant increase of the Hall parameter in the anode layer yields an increase of the anode potential drop and electron temperature. This occurrence is favourable for the development of ion-sound micro-instability, which, in turns, increases plasma thermalisation and heat transferred to the anode. Direct injection of neutral propellant in the anode region has proved to alleviate and/or delay the onset phenomena [8]; nevertheless no decisive results have been obtained, since the ionisation length in MPDT's exceeds the anode layer extent (of the order of the electron Larmor radius): an injection of ionised propellant in the anode region seems thus more appropriate to modify the anode layer condition, [9].

To assess the effectiveness of this last solution, a new MPDT (called "Hybrid Plasma Thruster" - HPT) has been proposed [10] and hence developed and tested in the framework of a joint activity between Centrospazio (Pisa, I) and RIAME of the Moscow Aviation Institute (RU) [11]. The HPT is an axisymmetric MPD thruster with an applied magnetic field, a central acceleration chamber and a peripheral ionisation chamber, where a fraction of the propellant is ionised by a secondary discharge and then injected in the main chamber throughout a semi-transparent anode (see the following paragraph for a detailed description). Two almost identical prototypes have been developed and are currently under testing in each laboratory.

At RIAME, using nitrogen as propellant, the activation of the additional discharge in the ionisation chamber has led to a considerable discharge voltage decrease and to the attenuation of the voltage fluctuation with a typical frequency of 100 kHz, both with and without the external magnetic field [12].

At CS, the experimental activity illustrated so far was focused on the assessment of the HPT performance, injecting a fraction of the propellant from the ionisation chamber (argon, 10% of the main mass flow rate) without the activation of the secondary discharge [13]. At low power (100-400 kW), the application of an external magnetic field significantly increases the thrust. The increase seems mainly due to the Hall acceleration mechanism, although for high applied field, also the gasdynamic contribution to thrust could be not negligible. As a consequence, thruster performance with an applied field, in terms of specific impulse and thrust efficiency, is significantly increased with respect to a self-field operation. At high power (greater than 500 kW), depending on the intensity of the applied field, Hall contribution to thrust seems to be less and less important, and the thrust appears to be almost the same as in a self-field operation. In same cases (i.e. 660 mg/s, 40 mT) the applied field yields no significant performance increase, or even a decay. Pinch and Hall effects, which tend to rarefy the plasma in the external region of the acceleration chamber, are supposed to be the causes of this occurrence.

In the following, more recent performance results obtained on CS HPT, both with and without the activation of the ionisation chamber are illustrated and discussed.

EXPERIMENTAL APPARATUS

The experimental apparatus HPT, shown in Fig.1, is an axisymmetric MPD thruster with an applied magnetic field. The HPT presents a central hollow cathode (copper, 20 mm diameter, 50 mm length), an anode, consisting of a cylinder (aluminium, 200 mm inner diameter, 180 mm length) and eight straps, made of copper and eight peripheral hollow electrodes (copper, 12 mm in diameter each), all connected at a conducting plate. The straps which divide a central chamber from a peripheral chamber are shaped to get their surface parallel to the local externally applied magnetic field lines. The propellant can be injected both through the central cathode and the peripheral ones, sharing the total mass flow rate in any ratio between the two chambers. The peripheral electrodes can be used as auxiliary cathodes to pre-ionise the peripheral propellant by means of a secondary discharge between the cathodes and the anode. A 70-turns coil surrounds the thruster and can be powered in order to generate a magnetic field up to 100 mT on the thruster axis.

TEST EQUIPMENT AND PROCEDURE

The thruster is mounted on a thrust stand inside the Centrospazio IV3 vacuum chamber, capable of maintaining a back pressure before and during the pulse in the 10^{-4} mbar range. The electric power to the HPT is supplied by a Pulse Forming Network (PFN), connected as shown in Fig. 2 and arranged to supply quasi-steady current pulses 2.5 ms long. The PFN is capable instantaneous power of 100-800 kW in the primary circuit and of 5-40 kW in the secondary one. The propellant is injected by two separated gas feeding systems, one for the central cathode and the other for the peripheral cathodes, based on fast acting solenoid

valves, which provide gas pulses with long plateau after few milliseconds from valve activation. The steady mass flow rate and the time between valve activation and the steady mass flow condition were obtained experimentally as described in [14]. Mass flow rate uncertainty is within 5% of the measurement. The magnetic coil is supplied by the discharge of a 10 mF capacitor bank by means of an SCR. As shown experimentally, a quasi-steady magnetic field lasting about 10 ms is obtained after 25 ms from the SCR switching on. Moreover, tests have shown the magnetic field obtained during quasi-steady phase of the pulsed operation is the same as a continuous operation, provided a slightly higher current is supplied [15]. A laboratory-made digital device allows to set the sequence of the SCR and the solenoid valve activation in order to start the arc discharge when a steady condition is reached for both the applied magnetic field and the mass flow rate. The arc ignition is obtained by closing the main circuit by switching an ignitron on. The primary and secondary arc currents have been measured with two Hall effect current probes (LEM® LT 4000-S). To avoid anomalous discharge involving the vacuum chamber, the thruster electrodes are floating with respect to the ground and the arc voltage has been measured by measuring the potential of each electrode with respect to the ground by means of three high voltage probes (Tek 6015). The primary and secondary arc voltage is then obtained by subtracting the pertinent cathode voltage signal from the anode voltage signal. Fig.3 shows typical measured arc current and voltage signals for the primary chamber.
The thrust stand consists of two double pendulums, acting like a four–bar link, which leaves the thruster free to move only in the axial direction. The hinges at the ends of the bars consist of thin phosphor bronze straps, that, for small displacements, act as virtual hinges with negligible disturbances to the mobility of the system. The suspension is fixed at the vacuum chamber by means of a stiff frame. The thruster is attached to the suspension by means of two supports, as illustrated in Fig.5. A proximity transducer (Bently Nevada® 7200) is used to measure the mobile mass displacement. A computerized procedure has been developed to get the thrust input bit by knowing the mobile mass weight (about 34 kg) and measuring its motion law in a period around the shot, as shown in Fig.6. The input bits so obtained were then purged by spurious effects due to cold gas injection and the activation of the external magnetic field. These effects were previously measured by using the same procedure without the activation of the arc discharge. The method allow the net thrust impulse bit to be measured with an accuracy of about 10% of the value.

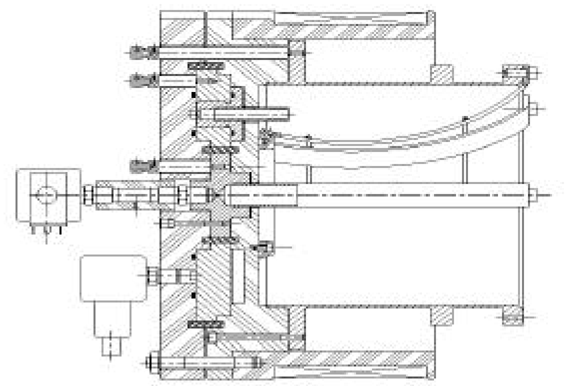

Fig. 1: Schematic drawing of the thruster assembly.

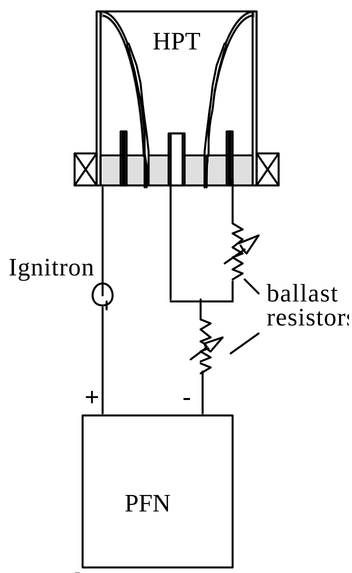

Fig.2: Electric circuit arrangement

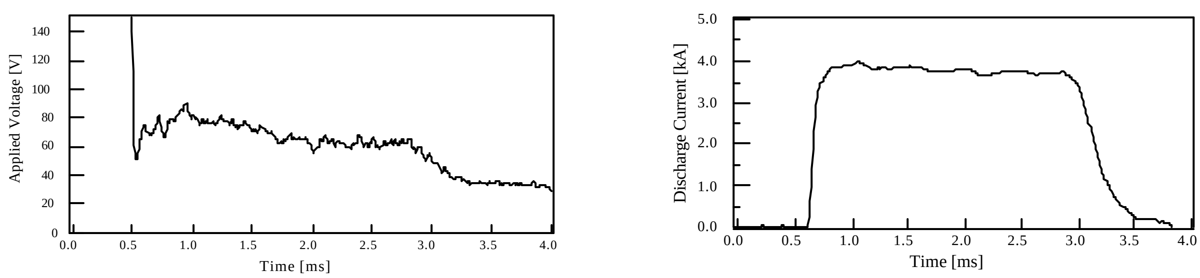

Fig. 3: Typical arc current and voltage signals (main discharge).

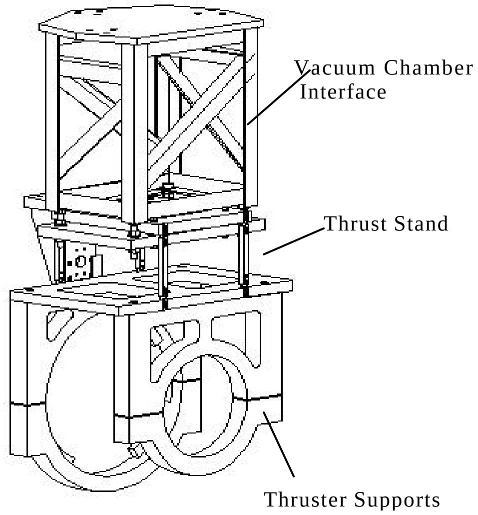

Fig. 4: Thrust stand layout.

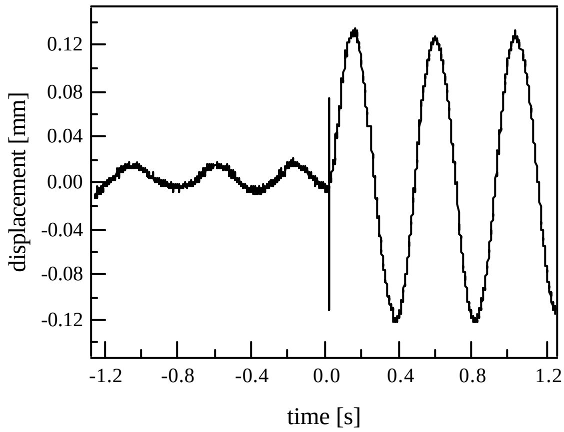

Fig. 5: Typical mobile mass displacement during a shot.

TEST RESULTS

Propellant injection mode effect

Electrical characteristic and thrust measurements. Starting from a benchmark configuration already illustrated in [13] (220 mg/s of argon, 200 mg/s injected by the central cathode and 20 mg/s by the peripheral injectors, referred as 200-20 condition) and maintaining the same total mass flow rate, the effect of the propellant injection mode has been investigated by increasing the fraction of propellant injected by the peripheral cathodes, without the activation of the secondary discharge. Two other combinations have been investigated: 180-40 (180 mg/s from the central cathode and 40 mg/s from the peripheral injectors) and 160-60. Tests have been performed both without and with an applied magnetic field (maximum applied induction field on the axis: 40 and 80 mT). For each shot, a current and voltage values were obtained as an average on a window 100 microseconds long taken in the middle of the pulse. Thrust is obtained by dividing the measured thrust impulse bit time the pulse duration, and thus the value represents an average thrust for each shot. Each data point in Figs. 6-11 was obtained as an average of the relevant values obtained from four-five shots at the same nominal condition (i.e. PFN charging voltage). Current and voltage measurements showed a good repeatability (the uncertainty is within the marker dimension). Error bars on thrust measurements include both the standard deviation and the measurement uncertainty.

The injection mode seems to not significantly affect the electrical characteristics, as illustrated in Figs. 6, 8, 10. The electrical characteristics at 160-60 and 180-80 tend to be slightly higher than the 220-20 characteristic, especially for the self field and B=40 mT operations. The effect on thrust seems more significant, as shown in Figs 7, 9, 11, with an increase ranging from 20% (high currents, high applied field) and 50% (low currents, no applied field) in the cases 180-40 and 160-60 with respect to 200-20.

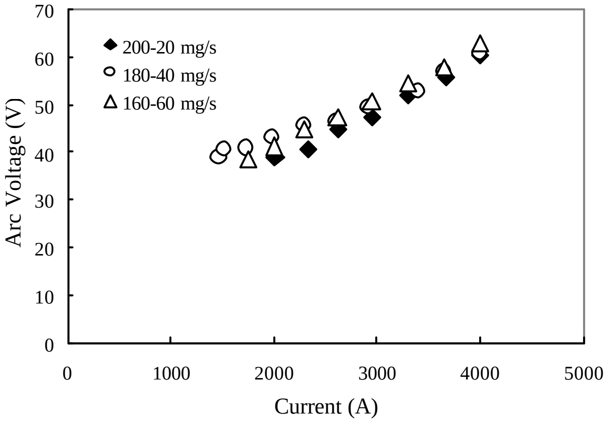

Fig. 6: Electrical characteristics, no applied field

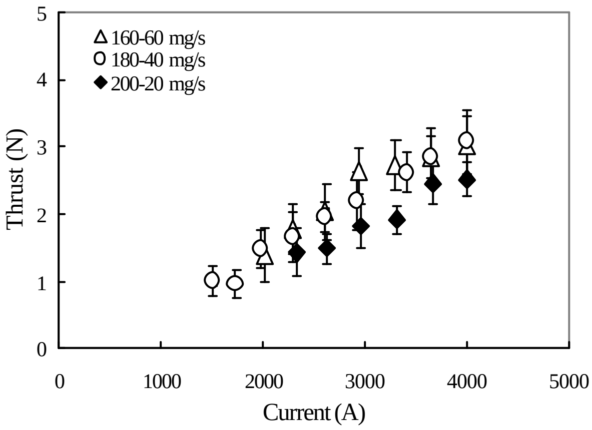

Fig. 7: Thrust vs current, no applied field

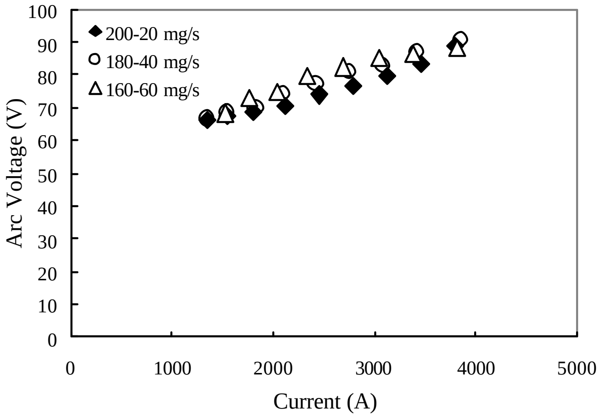

Fig. 8: Electrical characteristics, B=40 mT

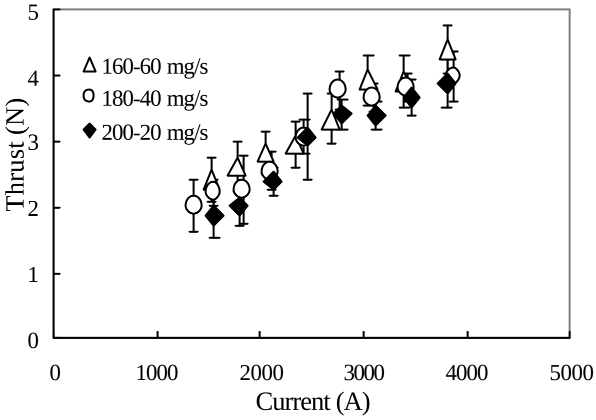

Fig. 9: Thrust vs current, B=40 mT

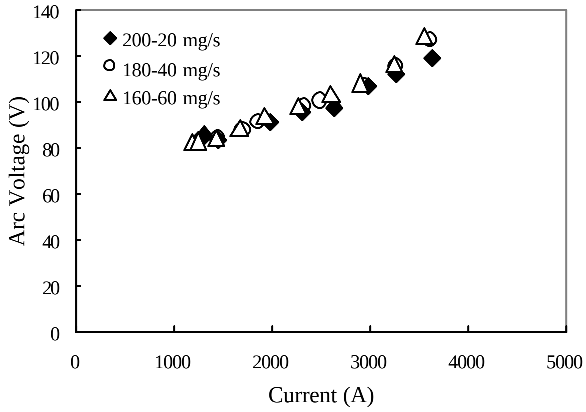

Fig. 10: Electrical characteristics, B=80 mT

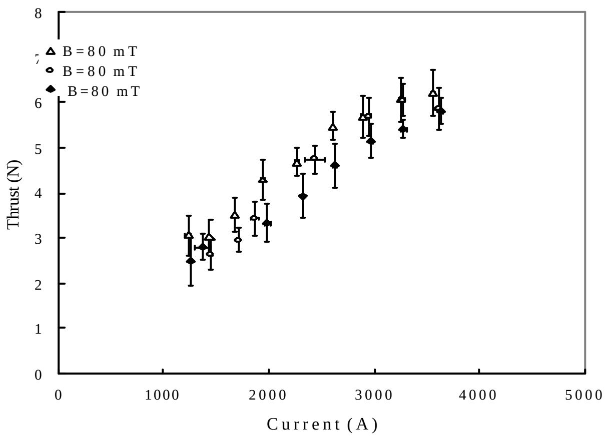

Fig. 11: Thrust vs current, B=80 mT

Performance trend. On the basis of the experimental results illustrated above, a trend analysis of the performance, in terms of specific impulse and thrust efficiency, has been done (Figs 12-17). The arc power has been calculated starting from the current-voltage data points of the electrical characteristics, by simply multiplying the current times the relevant voltage. Thrust as a function of current has been obtained by the experimental data applying a linear regression to each set of data points. Data dispersion and calculation procedure yield an average uncertainty of the calculated specific impulse and the thrust efficiency of about ±15% and ±30% respectively. Power supplied to the solenoid has been neglected.

Without external magnetic field (Figs 12 and 13), a significant improvement of performance, both in terms of specific impulse and thrust efficiency, is observed passing from 200-20 to 180-40. No significant improvements are observed with a further increase of the peripheral mass flow rate fraction (from 180-40 to 160-60).
With the applied magnetic field, the same the arc power, the effect of the mass flow rate injection mode on the specific impulse seems quite weak (Figs. 14 and 16). On the contrary, the thrust efficiency tends to increase significantly by increasing the mass flow rate fraction from the peripheral injectors (Figs. 15 and 17). Moreover, the increase has proven to be larger at low power than at high power, so that the thrust efficiency seems fairly independent on arc power, especially for the condition 160-60. Consequently, operation at low power seems more sensitive to the injection mode and combination with large fraction of propellant from the peripheral injectors are more favourable.
Maximum specific impulse obtained was 3000 s (160-60, 80 mT, 455 kW); maximum thrust efficiency was 22% (160-60, 80 mT, 315 kW).

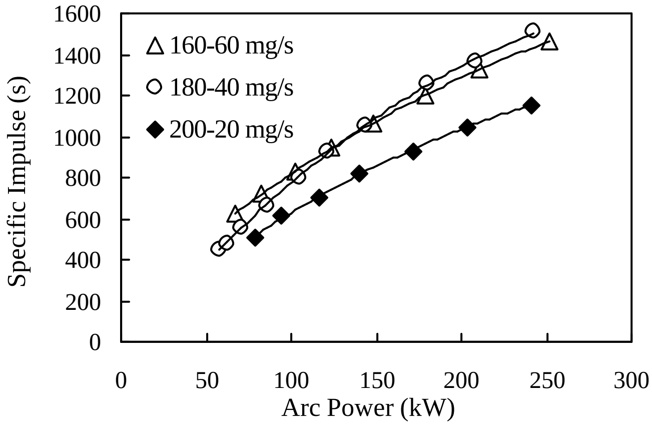

Fig. 12: Specific impulse vs. arc power, no applied field

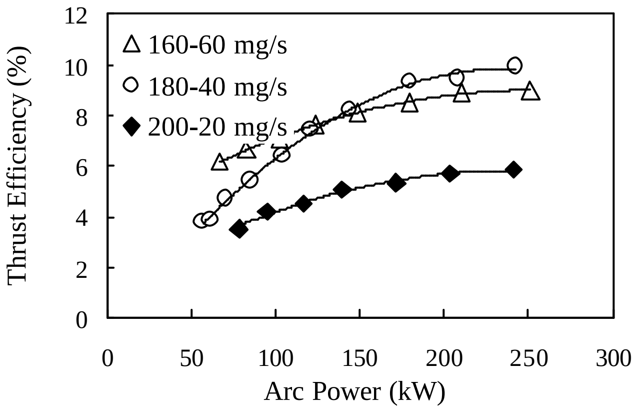

Fig. 13: Thrust efficiency vs. arc power, no applied fi

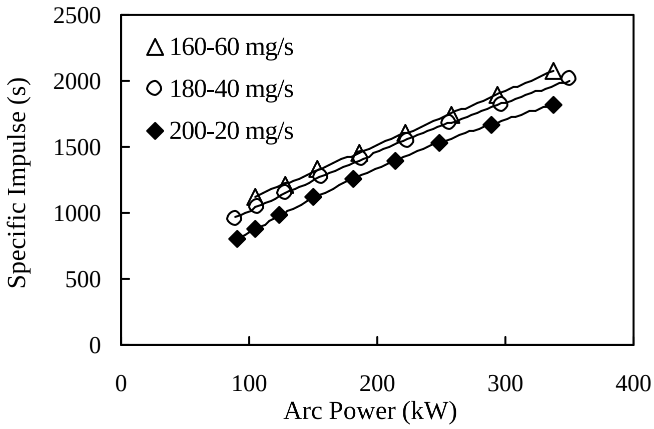

Fig. 14: Specific impulse vs. arc power, B=40 mT

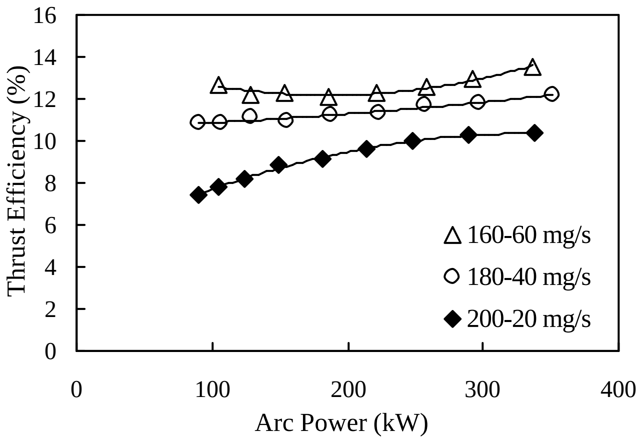

Fig. 15: Thrust efficiency vs. arc power, B=40 mT

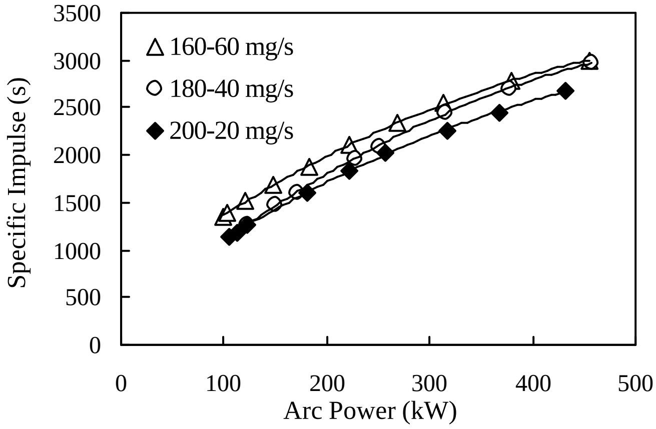

Fig. 16: Specific impulse vs. arc power, B=80 mT

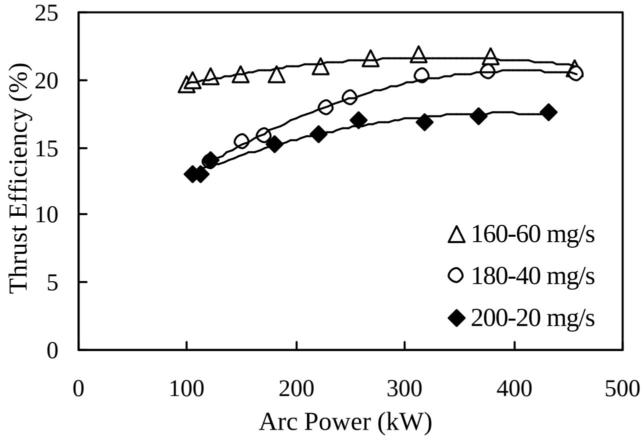

Fig. 17: Thrust efficiency vs. arc power, B=80 mT

Effect of the secondary discharge

Two experimental campaigns have been carried out on July and December 2002, in order to measure the effect of the activation of the secondary discharge on the thruster electrical characteristics.
In both campaigns the thruster has been operated with 220 mg/s of argon and three different injection modes (200-20, 160-60 and 120-100).
Tests have been performed with the thruster operated both without external magnetic field and with the application of a magnetic field value of 80 mT on the axis. During the last campaign also the values of 40 mT and 100 mT have been investigated only for the 200-20 gas injection condition.
As can be inferred from Figs. 18-20, while for the first campaign the activation of the secondary discharge ever led to a decrease of the I-V curve, especially with the application of the external magnetic field, this effect has been no more recorded during the second campaign. Moreover results indicate that in general the electrical characteristics referring to thruster operations without the activation of the pre-ionisation chamber are somewhat higher than previously measured.
In Figs. 21 and 22 the main discharge voltage signals recorded during the first campaign for the same operation conditions, with and without the activation of the secondary discharge, are compared. The signal referring to thruster operation with two discharges appears significantly lower than the other and voltage fluctuation result attenuated, confirming the beneficial effect of the secondary discharge activation. Fig. 23 reports the same comparison for typical signals recorded during the second campaign. Apart from the start-up phase, no significant differences can be observed between the two voltage signals.

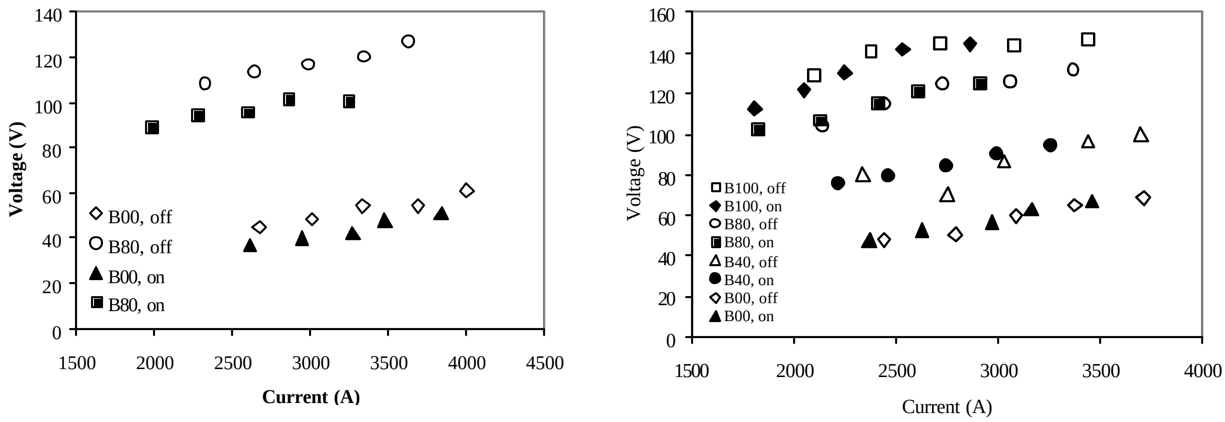

Fig. 18: Electrical characteristics from measurements performed on July (left) and December (right). Gas injection condition: 200-20

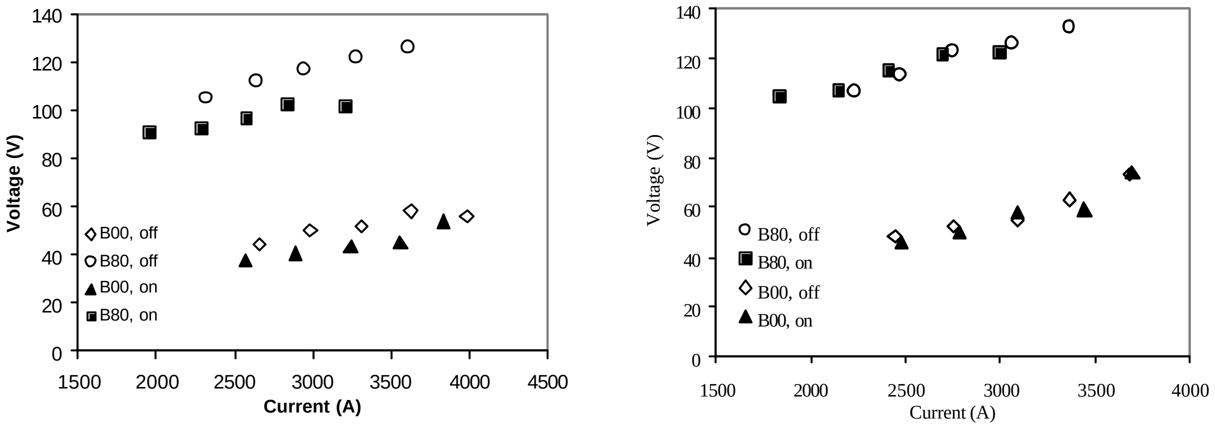

Fig. 19: Electrical characteristics from measurements performed on July (left) and December (right). Gas injection condition: 160-60

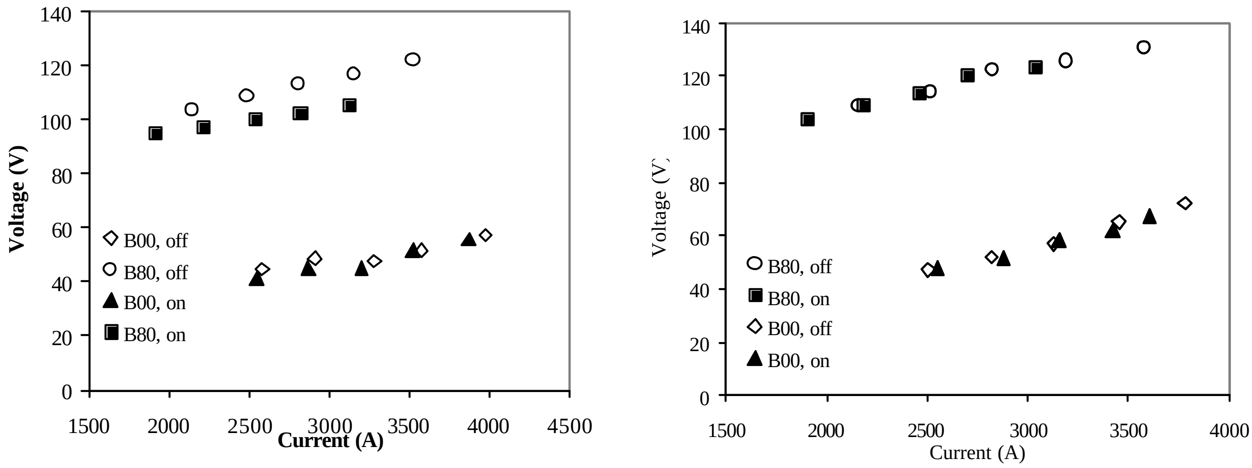

Fig. 20: Electrical characteristics from measurements performed on July (left) and December (right). Gas injection condition: 120-100

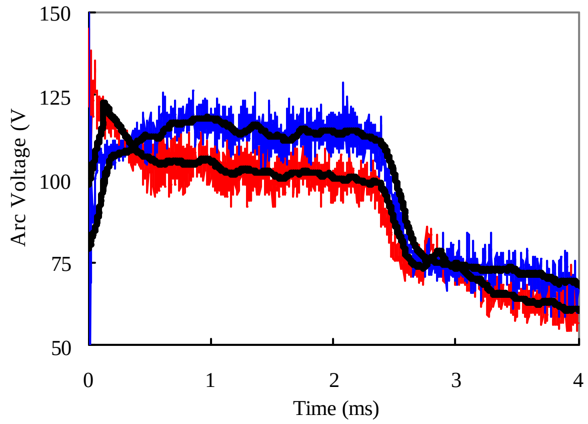

Fig. 21: Arc voltage at 2800 A, 80 mT , 120-100 gas injection mode, with (red) and without (blue) the activation of the secondary discharge, July 02.

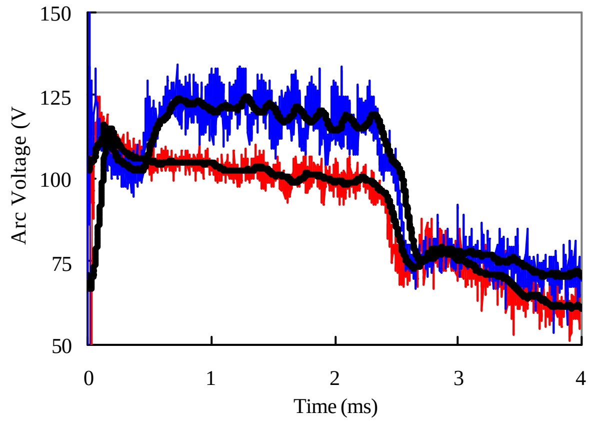

Fig. 22: Arc voltage at 3300 A , with 200-20 gas injection mode, with (red) and without (blue) the activation of the secondary discharge, July 02.

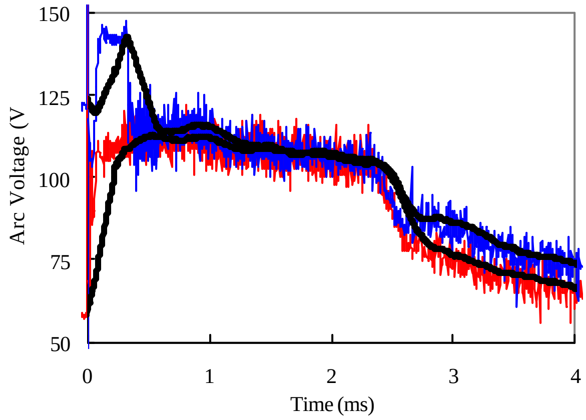

Fig. 23: Arc voltage at 2300 A, 80 mT , 120-100 gas injection mode, with (red) and without (blue) the activation of the secondary discharge, Dec. 02.

CONCLUSIONS

The results herein illustrated indicate the injection mode can significantly affect the performance of the HPT, also without the activation of the secondary discharge. The total mass flow rate the same, the performance increase by increasing the percentage of mass flow injected by the peripheral injectors, especially at low power. The improvement is mainly due to an increase of thrust, the same the power, rather than to a loss reduction.

So far, the activation of the pre-ionisation chamber has given contradicting results. The improvements observed in some occasion indicate the substantial effectiveness of the concept, but the current HPT configuration has proven to be not reliable enough for a thorough assessment of the thruster operation. As a matter of fact, the activation of all the peripheral cathodes at the same condition is not guaranteed by the current thruster design. Some observations of the thrust condition after testing have highlighted in some cases evidences of a not uniform operation of the peripheral cathodes (signs of concentrated arc attachment in some cathodes, char deposition close to some cathodes and not to others, etc.). To solve this problem, a new design HPT has been developed and soon will be ready for testing. The new thruster has the peripheral cathodes separated, each one with its own gas and electrical feeding system. This new configuration will allow the operation of the peripheral cathodes to be carried out independently on the main discharge and, above all, an operation check cathode by cathode could be made.

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