Parametric Test Results of a Low Power Arcjet

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A laboratory model of a low power arcjet has been tested at Centrospazio in the framework of an ASTP3 contract awarded by ESA to BPD Difesa e Spazio. As a part of this programme, extensive parametric tests were carried out on different thruster geometries in a power level up to 1.8kW. Nine different anode geometries were tested with different electrode gap settings. Each anode was characterized by a different constrictor diameter and length, while the other dimensions were fixed to a reference geometry. Hydrogen/nitrogen mixtures were used to simulate hydrazine and ammonia propellants. All tests were performed with a Pulse Width Modulated Power Processing Unit breadboard, developed at Centrospazio, with an integrated voltage pulse start-up circuit capable of controlling and limiting the current during the arc ignition. Tests on some electrode configurations were repeated with a Zirconium Diboride coating on the anode external surface in order to increase the infrared emissivity. A comparison between the experimental data relative to both anode configurations, coated and uncoated, are presented. Temperature measurements were made during thruster operation by means of thermocouples and a pyrometer. The experimental data were compared with those calculated as a part of a thermal analysis carried out with the MARC code.

Introduction

Electric Propulsion systems based on arcjet engines fed with storable and unstorable propellants at power levels ranging from 100 kW to less than 1 kW are currently under development in the USA, Europe and Japan. In this framework, since 1988 Centrospazio has carried out the development of a 1 kW arcjet as part of an Advanced Space Technology Program (ASTP) contract awarded to BPD Difesa e Spazio by ESA, with Centrospazio acting as a subcontractor. This project represents the most important medium term electric propulsion programme to be carried out in Italy over the next few years and will receive the largest allocation of funds from both ESA and ASI (Italian Space Agency). A follow-on program for the development of 1.8 kW advanced engineering arcjet model for flight qualification is planned to start in fall 1993, with Centrospazio involved in the technology development and diagnostics application. Within the ASTP programme different arcjet models have been tested: the MOD-A engine, developed at Centrospazio and presented in this paper, and the MOD-B engine, developed by BPD. Engine testing at Centrospazio focused on the definition of the operational envelope and parametric performance mapping using nitrogen, hydrogen and mixtures of these gases. Activities at BPD mainly focussed on catalytically decomposed hydrazine and on endurance testing.

This paper describes the results of extensive parametric tests on different engine configurations. Each configuration was characterized by varying the constrictor diameter, length, and the electrode gap, in order to provide information on the engine operational envelope. A number of tests were carried out both with and without Zirconium Diboride coating on the anode external surface in order to increase its infrared emissivity. Hydrogen and nitrogen mixtures of proper compositions were used to simulate hydrazine and ammonia propellants. All tests were carried out with a Pulse Width Modulated Power Processing Unit breadboard with an integrated voltage pulse start-up circuit capable of controlling and limiting the current during arc ignition.

Apparatus

Thruster

The thruster was designed and developed at Centrospazio in the framework of the ASTP programme (Fig. 1). The body of the test engine was carefully designed in order to simplify critical part replacement and cathode positioning, while the radiation-cooled nozzle was already oriented towards a possible flight configuration.

The propellant enters the engine through a stainless steel tube at the centre of the engine body, flows around a spiral path machined into a boron nitride insulator and is injected at a 54° angle into the plenum chamber through six tangential injection ports with a total area of 1.5 mm². The anode and the cathode are made of 2% thoriated-tungsten rather than pure tungsten because its lower work function.
increases the cathode thermionic emission and reduces the temperature of the arc attachment point on the anode. A restriction of the anode cross section works as a thermal dam designed to reduce heat conduction to the rest of the thruster.

The typical geometries of the electrodes and the injector are shown in Fig. 2. Nine different test anodes were manufactured, mostly by STV Spa (Brescia, Italy). Five of these were plasma-spray coated by GALAXY Flame Spray Spa (Brescia, Italy) over their external surfaces with a 0.25 mm thick layer of Zirconium Diboride (ZrB2), characterized by a particle size of about 10 μm and 99.5% purity. This coating is intended to improve the radiative heat dissipation of the anode by increasing its thermal emissivity, without exceeding the size limitations adopted in the design phase (22 mm external diameter). The various test anodes have the same general shape (45° semi-aperture conical convergent and 20° conical divergent) and area ratio (113), but different constrictor diameters and lengths in order to carry out a series of parametric tests. A crucial manufacturing aspect was the realization of the constrictor hole, obtained by means of a properly designed WC-drill, without any electroerosion process. Due to manufacturing difficulties, the real dimensions of the anodes are slightly different from their nominal values. However, these minor discrepancies are believed to be insignificant for parametric comparison of the various configurations. Tab. 1 summarizes the characteristic dimensions of the different anodes.

The cathodes were obtained from commercially supplied 164 mm long and 3 mm diameter rods for TIG welding. The cathode tip was conically sharpened to 60° internal semi-aperture angle. Allumina and boron nitride plugs were used to electrically insulate the electrodes. The thruster body was fabricated from TZM, a Molibdenum alloy with Titanium and Zirconium, easier to work than pure Molibdenum. Grafoil washers were used for the seals and to protect the boron nitride surfaces.

The nozzle flow pressure was measured by a transducer connected to a specially modified anode (Fig. 3) by means of:
- a stainless steel holder to support the transducer;
- an electrical insulator to prevent transducer damage due to the high voltage pulse at engine start-up;
- a stainless steel tube for connection to the anode tap, and thermal insulation from the transducer.

The tube was brazed on the tungsten anode and bonded on the ceramic insulator. The pressure was sampled from a 0.5 mm diameter tap hole drilled in the plenum chamber, just in the middle of the cylindrical channel. For comparison, the constrictor diameter of the anode was 0.9 mm.

Vacuum Facility

The Vacuum Facility used at Centrospazio for arcjet testing was provided by ESA as part of the ASTP programme. The Facility consists of a steel vacuum chamber 1.25 m in diameter and 1.75 m in length. A 1.25 m diameter manifold tube connects the chamber to a pumping system comprising two Edwards 30B5 oil booster pumps backed by four Edwards HISC3000 rotary pumps, with a total pumping speed of 20,000 l/s at 10^4 mBar background pressure. The leakage rate of the chamber has been repeatedly checked and found to be on the order of 1.1x10^2 mbar l/s, less than 0.1% of the normal pumping speed.

Propellant Feed System

The Propellant Feeding System (PFS) was designed to supply the arcjet with argon, nitrogen, hydrogen, or finely controlled mixtures thereof (to simulate hydrazine decomposition products or ammonia). The mass flow rates of each gas were regulated by TYLAN thermoresistive controllers model FC 280S, 1% F.S. accurate in steady state conditions, and capable to restore the flow rate to within ±2% from the set point after 0.4 to 0.8 s from the beginning of a transient. Supply gases were filtered by Messer-Grishaim Oxisorb filters, in order to ensure an oxygen-free propellant to the arcjet.

Power Supply Unit

A breadboard of a Power Conditioning Unit developed at Centrospazio was used for the parametric tests (Table 2). From a general point of view the PCU is a Pulse Width Modulated Current Mode Controlled converter with adjustable switching frequency in the 16 to 60 kHz range. The Power Stage (Fig. 4) was manufactured by CEV-Viareggio (Lucca, Italy). It is a DC-DC converter (buck) with a push-pull topology supplied by the laboratory 50 VDC Power Supply simulating the spacecraft power bus. The Control Stage is a PWM/Current Programmed Mode controller comprising a fast inner feedback loop on the current (characteristic of the CPM converter) and a slower outer loop incorporating a PI controller.

The unit is provided with a specially designed start-up circuit that controls and limits the initial discharge current after breakdown. This start-up circuit can also be used independently of the PCU, in conjunction with an ordinary laboratory power supply with a ballast resistor electrical configuration. The circuit applies high voltage ignition pulses by means of a pulse transformer with a 7:1 conversion ratio. A 25 VDC power supply from the PCU power bus energizes the pulse transformer by means of a MOSFET electronic switch. When the switch goes OFF the extra-voltage generated in the primary coil of the transformer is reflected to the secondary one, which is in series with the arcjet.

In this subsystem the energizing rate of the pulse transformer is of crucial importance. It is proportional to the peak value of the primary current during the ON time of the switch. In turn, the peak current affects the maximum voltage generated across the snubber capacitor, which forms a series resonant group with the primary magnetizing inductance during the OFF time. The MOSFET BDV fixes an upper limit to this overvoltage and then to the secondary reflected one. The adopted components allow an open voltage pulse of 2.8 kV with up to 60 mJ energy delivery to the arc.
Diagnostics and Instrumentation

Data Acquisition System - The D.A.S. is based on a PC/DOS architecture. A 14 bits card performs the A/D conversion. The card scans data on up to 16 channels at a sample frequency adjustable up to 2 Hz. Each channel acquires analog signals from 0 to 5 V DC and converts them with an accuracy of ± 0.1%. All signals were analogically filtered before the A/D conversion. The acquired data are displayed on the monitor and stored in ASCII format; all data processing software was developed in house. The data are then reduced in graphical and tabular form in a Macintosh system.

Thrust Balance - A swing arm balance was designed and manufactured for the arcjet parametric tests (Fig. 5). It consists of a vertical lever gimballed on a knife edge hinge and of a load cell. The lever is provided with two arms to form a L-shaped figure. The vertical arm supports the engine on a edge; a horizontal arm, with a hardened metal cone on the forward tip, presses on the load cell. To avoid friction, the cone does not apply the thrust directly on the load cell, but on a gliding support. Due to the length-ratio between the arms of the L-shaped lever, an amplification of the thrust measurement is obtained (11.70 times). The whole assembly is mounted on a fixed plate at the top of the vacuum chamber. Contact between the lever and the load cell is ensured by an adjustable preload.

Voltage and current sensor - Voltage measurements were made by means of a calibrated 1:47.2 voltage divider, located outside the vacuum chamber, just near the electrical connections of the feedthroughs. The length of the cables between the engine electrical fittings and the electrical feedthroughs inside the chamber was about 2 meters. The line impedance was some orders of magnitude lower than that characteristic of the arc, so the measured voltage is essentially the true voltage drop across the electrodes.

The current was measured by means of a Hall effect sensor located on the cathode line just outside the vacuum chamber. Its output was frequently compared with that of a similar sensor located on the PCU output line, and the measurements agreed. Transient measurements of the electrical quantities during start-up operations were monitored by a Tektronix 2221 Oscilloscope, and were made with high voltage probe Tektronix P6015 (1000x) or a low voltage probe P6109 (10x).

Pressure and temperature sensors - Two pressure transducers were used for the testing activity. A KULITE HKM-375 for the feedline pressure and a XTE -190 to measure the plenum chamber pressure. The feedline pressure was measured inside the vacuum chamber about 2 m before the fluid connection to the engine body. For the nozzle flow pressure measurement a special assembly was designed and manufactured on the adapted anode already described.

Background pressure in the vacuum chamber was measured by means of the Pirani gauge of the vacuum facility. The gauge is located on the outlet of the roughing line of the rotary pump, near the gate valves above the booster pumps. Comparison with the measurements obtained with an ionization gauge located in the test chamber showed a slightly lower vacuum level in the test cell with respect to vacuum chamber.

Temperature measurements were carried out by a combination of thermocouples and an ACCUFIBER optical Pyrometer with an operating range from 500 to 3000 °C and 2 mm spatial resolution. The acquisition and processing of the signals is performed by a proper controller (ACCUFIBER Mod. 10) connected to the sensors by an optical fiber wire and capable to perform up to 10 readings/sec with a temperature resolution of 0.1 °C. The pyrometer was mounted in the vacuum chamber on a movable support positioned by a manually operated rotating feedthrough. This arrangement enables the Pyrometer to be axially moved in order to take measurements at different points along the arcjet nozzle.

Four K-thermocouples were used to measure the temperature on the body of the engine. The thermocouples were insulated with an epoxy sheet and externally coated with Incolnel, in order to prevent the introduction of electrical noise through the contact. The signals were 10x amplified with an instrumentation amplifier INA101 from Burr Brown Corp., and analogically filtered before the A/D conversion.

Test Procedure

For each geometrical configuration of the thruster, the operating points were characterized by varying two parameters, the mass flow rate and current level, and by the corresponding voltage and thrust measurements. The information and the data gathered during the test were organized in proper form for performance analysis and presentation in terms of power input, specific impulse, specific power, thrust efficiency. The test series was organized as follows.

Thrust preparation - The thruster was assembled according to the sequence specified by the technical drawings. The cathode gap was set by fitting the thruster and a micrometer on the same support structure, putting the cathode in contact with the anode and then withdrawing the micrometer and cathode to their assigned position. During the tightening of the Swagelock fittings the cathode moves forward; the micrometer reading was then re-verified.

Installation in the vacuum chamber - The arcjet is mounted on the thrust stand inside the vacuum chamber and connected to the power supply, the gas feeding system, and the thermocouples. The proper insulation between the two electrodes and between each electrode and the mounting structure/chamber was tested (a floating electrode configuration was chosen).

Instrumentation calibration - Upon reaching the test vacuum conditions (1.0x10^-4 mbar), calibration of the instrumentation was carried out. All these data were recorded in the calibration file.
Testing - The following sequence was adopted:

1. The load cell is calibrated with and without the calibration mass. Then the lever is applied to the cell.
2. The gas feeding system is turned on and cold flow measurements are carried out at 20, 30, 40 and 50 mg/s mass flow rates for a mixture simulating hydrazine.
3. The PCU is turned on and the ignition parameters are adjusted:
   - $N_2 + 2H_2$ mixture at 30 mg/s mass flow rate;
   - 10 A current;
   - 16 kHz PCU DC-DC converter frequency;
   - 2.8 kV ignition impulse.
4. The engine is started on.
5. After a 30 minutes warm-up period to reach thermal equilibrium, the lever is removed from the load cell in order to zero the thrust stand, and then applied again to carry out the measurements. The thruster is turned off for recording the actual preload value on the load cell. Finally the thruster is turned on with the same ignition parameters as in previous point # 3.
6. After waiting 5 minutes, the current is increased in steps of 2 A up to 16 A. The 10 A operating point is then repeated for comparison. Each operating point is maintained for 5 minutes for stabilizing the anode thermal conditions.
7. The mass flow rate is increased to 40 mg/s and then 50 mg/s. The procedure described at the previous point is repeated. After each series of measurements, operation at 30 mg/s and 10 A was always restored for comparison.
8. The mass flow rate is subsequently changed to 20 mg/s or 25 mg/s depending on the arc stability conditions and, if possible, the standard current values are repeated.

When the thruster operation appeared sufficiently stable the measurement range was enlarged both to lower (in some cases down to 3A) and higher current levels (up to 22A).

Thrust inspection and dismantling - After the tests a series of photographs of the electrodes was taken in order to examine the state of erosion.

Data reduction and analysis - Data gathered during the tests were stored in ASCII files on a PC/DOS mass memory after each 1200s sampling. The data were converted and processed on a Macintosh system. All data were organized in a proper data base and presented in form of plot charts. The average of all the data measured during the last minute (of the 5 min operating point) was computed and presented in tabular form. The values measured were then analyzed and reduced in the form of diagrams for ease of comparison.

Thermal Analysis

The MOD-A thermal analysis was carried out with the MARC code. The geometry of the engine was assumed as axi-symmetric; all of the arcjet components were modelled. Particular attention was paid to the modelling of the contact between the elements. The heat exchange mechanisms considered in the computations included: thermal conductivity, radiation from the external surfaces, engine interface heat sinks, and the convective internal heat transfer between the engine and the propellant. Material properties were considered as temperature dependent in the range of 300 - 3000 K. The assumed boundary conditions included: the radiation of the external surface to a black-body at a temperature of 298 K in one case and 3 K in another. The temperature of the cathode tip was assumed to be 3273 K. A given heat flux on the arc attachment area of the nozzle was assumed, as a function of the engine power. The analysis was carried out for steady state conditions both with and without the ZrB$_2$ coating on the anode surface. The mesh was characterized by 459 nodes and the four-node element (No. 40) of the MARC code was used to model the parts (Fig. 6).

Computations were made for the actual anode geometries ($\Theta = 0.7$ mm., $L/\Theta = 2$, Gap = 0.8 mm.) at 784W input power and 30mg/s mass flow rate. A 220 W anode heat input and a 85 W convective cooling of the inside of the thruster were assumed. Thus the net heat flux input to the engine was 145W, about 18% of the arc power. The calculated values on the nozzle are presented in Fig. 7, and agree within 3% with the experimental measurements (Fig. 11). Only for one, less representative, point the discrepancy between the calculated and measured temperature was higher (15%).

The same case, but with the thruster radiating to the free space at 3 K, was also calculated (Fig. 8). The overall temperature decreased by about 80 K.

The case of a net heat flux input of 215 W was also calculated, both for the case of an uncoated anode (Fig. 9) and with a coating of total emissivity of 0.4 (Fig. 10). For the same electrical efficiency (18%) the total computed arcjet power is 1190 W. The comparison with the experimental measurements for the same reference geometry ($\Theta = 0.7$, $L/\Theta = 2$, Gap = 0.8) with anode coating is shown in Fig. 12.

Test Results and Discussion

A series of tests were conducted on different engine configurations in order to investigate their performance limits and operating envelope. Each configuration was characterized by a different nozzle (anode) and electrode gap setting. The same cathode design was adopted for each test, but a new piece was employed to replace the old one after each test. The configurations tested are listed in Table 1. These configurations were chosen to evaluate the effects of constrictor length, constrictor diameter and electrode gap on the engine performance. The engine was tested at power levels of up to 1.8 kW operating with simulated hydrazine. Five anodes were tested with and without the zirconium diboride coating to compare performance and thermal behaviour. Due to manufacturing and assembling difficulties, the actual geometry of the constrictor and electrode gap were slightly different from
the nominal configuration. However, these discrepancies are not believed to have a significant effect on the results of parametric tests.

In all tests the geometries characterized by the smaller diameter (0.5 mm) gave the best results in terms of propulsive performance (specific impulse and total efficiency), and therefore have been the main focus of the tests.

The V/I characteristics obtained at 30, 40 and 50 mg/s for these anodes (uncoated) with different constrictor lengths (L) but the same electrode gap (0.45 mm) are compared in Figs. 13-15. The anode with a 1 mm constrictor length showed an average voltage drop 20 V higher than the one with a 0.25 mm long constrictor for all the mass flow rates. This measurements allows to calculate a 26 V/mm voltage drop gradient in the constrictor length. This value is similar to the trends measured for L = 0.25 to 0.5 (23 V/mm) and L = 0.5 to 1.0 (30 V/mm). The voltage was generally higher at low currents (43 V/mm at 6 Amps) and tended to decrease at higher currents. No significant difference in propulsive performance were detected. Fig. 16 shows the P' characteristics for the same operating points as the electrical V/I characteristics. All of the points are almost aligned; those obtained at higher mass flow rate showed a slightly better performance, particularly at high specific powers. This tendency was already demonstrated in previous works, and is related to the associated increase of the efficiency (as shown in Fig. 17). This behaviour is believed to be due to the higher flow pressure, which favours the recombinaction of the dissociated species in the nozzle, resulting in a reduction of the frozen flow losses. This assumption is confirmed by the results obtained for different constrictor diameters but the same cathode gap and L/Ø ratio. Fig. 18 shows the specific impulse obtained at 30 and 50 mg/s with anodes characterized by increasing constrictor diameters (Ø=0.5, 0.7 and 0.9mm) and the same L/Ø (~ 0.45 mm gap). As one can see, the Isp obtained for the narrower anode is considerably higher than the others. The same trend is evident in the efficiency Fig. 19. The decrease of pressure in the plenum chamber also results in a lower voltage drop (Figs. 20-22).

An increase of the electrode gap gives a higher voltage drop with respect to a similar increase of the constrictor length. Figs. 23-24 show the V/I characteristics measured at 30 and 50 mg/s for the geometry characterized by Ø = 0.5, L/Ø = 0.5 and Ø = 0.75, L/Ø = 0.5 with 0.45 and 0.8 mm gaps. For both geometries the trend corresponds to an average increase of 33 V/mm upon all the mass flow rates. Operating points are again aligned in the Isp/P' plane and the efficiency also shows the same trend as the specific power (Figs. 25-26). In principle one can obtain the desired electric power (at a given mass flow rate) by selecting the electrode configuration so as to meet the required voltage and current levels. A 0.5 mm constrictor diameter seems to be preferable with respect to the others from the standpoint of propulsive performance. However, erosion seems to be a major concern. Pictures of the constrictor diameter for Ø=0.5, L/Ø=1 and 2, and for Ø=0.7, L/Ø=2 were taken after about 10 hours of operation (Figs. 27-29). The narrower anodes showed some damage. The circular constrictor geometry changed its shape due to local melting and showed a quasi-elliptical section.

The performance parameters measured for a given geometry are similar before and after the surface coating. Figs. 30-31 show data obtained for Ø=0.5, L/Ø=2 with a 0.45 mm gap.

Testing of the different geometries always included data at mass flow rates of 30, 40 and 50 mg/s. When the flow pressure is increased, the engine operation is more stable. Figs. 32-33 compare the signals measured by the D.A.S. for Ø=0.7, L/Ø=2, gap = 0.45mm and mass flow rates of 30 and 50 mg/s. The voltage oscillations (and consequently, the power, due to the current control mode of the P.C.U.) at low mass flow rates are more frequent than at higher mass flow rates. At the same operating point but for a different nozzle geometry (with the narrower constrictor diameter, 0.5mm) the engine operation was more stable also at low mass flow rates (Figs. 34-35). For 0.5mm diameter nozzles stable operation at 20 mg/s was observed. Figs. 36-37 show the performance traces of the parameters monitored by the D.A.S. for two anodes at similar power levels (Ø=0.5, L/Ø=2, gap 0.45mm, after 8 hours of operation; Ø=0.5, L/Ø=1, gap 1.0mm, after 22 hours of operation).

The performance characteristics measured for the Ø=0.5, L/Ø=2 anode with 0.45mm gap at 1.26 kW power are summarized in Table 3.

As discussed above, the pressure level of the nozzle flow plays a key role in arcjet performance. A specific effort was made to measure the pressure in the plenum chamber and compare it to the feedline pressure. The anode characterized by Ø=0.9mm and L/Ø=1 was fitted with a pressure measurement tap. The data obtained at 40 and 50 mg/s mass flow rates are shown in Fig. 38. The pressure level during engine operation is more than double that measured in cold flow condition. The pressure increases with the power due to the flow blockage induced by a bigger arc. The pressure drop between the feedline pressure measurement point and the plenum chamber was 23% of the feedline pressure both for 40 and 50 mg/s during the engine operation.

The controlled overvoltage pulse technique, developed to start the arcjet thruster, was characterized by using the start-up unit of the dedicated PCU. In order to focus attention on the starting system only, an arc ignition sequence was carried out with the PCU main power supply turned off. The arc current transient as measured for three energization levels of the pulse transformer are shown in Fig. 39 (Y scale = 2A/division, X scale = 5micro-s/division). The level of the current spike depends on the energization time only.

Ignitions with the main power supply switched on were performed with nitrogen, hydrogen, simulated hydrazine and ammonia. The initial discharge current was always limited to few amperes depending on the energization level of the pulse transformer. A typical current start-up transient
with the PCU switching frequency rated at 18 kHz is shown in Fig. 40 (Y scale = 2.5A/division, X scale = 20 micro-s/division). The initial discharge current is about 2 A. The percentage of successful starts at the first attempt was about 95% and steady state operation was achieved for propellant mass flow rate ranging from 30 to 50 mg/s regardless of the switching frequency. The steady state current ranged between 6 to 14 A. Figs. 41-42 show a typical start-up transient for voltage and current. The different time scale allows to illustrate the special features of the technique developed. Fig. 41 shows the initial current at start-up and the voltage pulse (1.6 kV is the measured arc breakdown voltage). The data in Fig. 42 were obtained under similar conditions but on a larger time scale. The voltage pulse cannot be appreciated but, on the other hand, it is clear that the current overshoot and crossover are above the design values. By proper choice of the starting parameters it has been possible to reduce the current overshoot below 50% of the setpoint current level.

The thruster has been successfully tested with a breadboard PCU also developed at Centrospazio.

On the basis of the test activity on the thruster, the measured performance characteristics are in line with system requirements for future spacecraft application. In particular, an average specific impulse greater than 500 s was recorded for simulated hydrazine at mass flow rates of 30 to 40 mg/s, a power level of 1260 W and with a thrust efficiency between 0.32 and 0.35. However, this performance level was obtained for a geometrical configuration which appears critical for electrode life. Additional studies on the erosion process and the development of reliable start-up techniques are required for further development of the engine.

Concluding Remarks

In the framework of activities carried out at Centrospazio for the ASTP-3 programme, an arcjet thruster was designed and manufactured to carry out a series of parametric tests on different engine configurations in order to investigate their performance limits and operating behaviour. The thruster has been successfully tested with a breadboard PCU also developed at Centrospazio.

On the basis of the test activity on the thruster, the measured performance characteristics are in line with system requirements for future spacecraft application. In particular, an average specific impulse greater than 500 s was recorded for simulated hydrazine at mass flow rates of 30 to 40 mg/s, a power level of 1260 W and with a thrust efficiency between 0.32 and 0.35. However, this performance level was obtained for a geometrical configuration which appears critical for electrode life. Additional studies on the erosion process and the development of reliable start-up techniques are required for further development of the engine.

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References

Table 1  Tested configurations

<table>
<thead>
<tr>
<th>L = Constrictor length</th>
<th>Ø = Constrictor diameter</th>
<th>G = Gap Length</th>
<th>* = Coated with ZrB2</th>
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<tbody>
<tr>
<td>0.9</td>
<td>G = 0.46</td>
<td>G = 0.4</td>
<td>G = 1.6 *</td>
</tr>
<tr>
<td>0.7</td>
<td>G = 0.45 G = 0.80</td>
<td>G = 0.5</td>
<td>G = 0.5 G = 0.80 *</td>
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<tr>
<td>0.5</td>
<td>G = 0.47 G = 0.80</td>
<td>G = 0.45 G = 0.45 G = 0.80 G = 1.03 *</td>
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Table 2  Breadboard PCU specifications

<table>
<thead>
<tr>
<th>PCU/POWER BUS INTERFACE</th>
<th>PCU/ENGINE INTERFACE</th>
<th>OPERATING FEATURES</th>
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</thead>
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<tr>
<td>Input voltage 45 to 55 Vdc</td>
<td>Start-Up Voltage peak 1.5 to 2.8 kV</td>
<td>Operation in current control mode</td>
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<td>Input current &lt; 50 A</td>
<td>Pulse width 5 to 10 μs</td>
<td>Switching frequency adjustable from 16 to 60 kHz</td>
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<td>Current ripple &lt; 1%</td>
<td>Current crossover 0.1 to 2 ms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy release &gt; 60 mJ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial discharge current &lt; 3 A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Current ripple &lt; 15% peak to peak</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Efficiency &gt; 88%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Response time &lt; 1 ms</td>
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Table 3  Characteristics performance measured at 1.26 kW
( Ø = 0.5 mm, L/Ø = 2, Gap = 0.45 mm )

<table>
<thead>
<tr>
<th>M.F.R. (mg/s)</th>
<th>Isp (s)</th>
<th>T(mN)</th>
<th>Eff</th>
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<tr>
<td>50</td>
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<tr>
<td>25</td>
<td>554</td>
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Fig. 1 MOD-A Arcjet assembly.

Fig. 2 Cathode, anode and injector configuration.
Fig. 3  Push-pull power stage and startup circuit.

Fig. 4  The thrust stand.

Fig. 5  Adapted nozzle for pressure measurements.
1) 2.821*2  
2) 4.419*2  
3) 6.017*2  
4) 7.616*2  
5) 9.214*2  
6) 1.081+3  
7) 1.241+3  
8) 1.400+3  
9) 1.560+3  
10) 1.720+3  
11) 1.880+3  
12) 2.040+3  
13) 2.200+3  
14) 2.359+3  
15) 2.519+3  
16) 2.679+3  
17) 2.839+3  
18) 2.999+3

**Fig. 6** Arcjet mesh for the thermal analysis.

**Fig. 7** Nozzle temperature profiles for 145 W net heat flux input to the anode.

**Fig. 8** Nozzle temperature profiles for 145W net heat flux input to the anode radiating to the space at 3K.

**Fig. 9** Nozzle temperature profiles for 215 W net heat flux input to the anode.

**Fig. 10** Nozzle temperature profiles for 215 W net heat flux input to the anode (coated $\varepsilon = 0.4$).
Fig. 11 Comparison between predicted (in parenthesis) and measured temperatures for 145 W net heat flux input.

Fig. 12 Comparison between predicted (in parenthesis) and measured temperatures for 215 W net heat flux input.

Fig. 13 Electric characteristics for 30 mg/sec mass flow as function of constrictor length (\( \Omega = 0.5 \text{ mm}, \ G = 0.45 \text{ mm} \)).

Fig. 14 Electric characteristics for 40 mg/sec mass flow as function of constrictor length (\( \Omega = 0.5 \text{ mm}, \ G = 0.45 \text{ mm} \)).

Fig. 15 Electric characteristics for 50 mg/sec mass flow as function of constrictor length (\( \Omega = 0.5 \text{ mm}, \ G = 0.45 \text{ mm} \)).

Fig. 16 Specific impulse vs. specific power as function of constrictor length (\( \Omega = 0.5 \text{ mm}, \ G = 0.45 \text{ mm} \)).
Fig. 17 Efficiency vs. specific power as function of constrictor length (Ø = 0.5 mm, G = 0.45 mm).

Fig. 18 Specific Impulse vs. specific power as function of constrictor diameter (L/Ø = 0.5, G = 0.45 mm).

Fig. 19 Efficiency vs. specific power as function of constrictor diameter (L/Ø = 0.5, G = 0.45 mm).

Fig. 20 Electric characteristics for 30 mg/sec mass flow as function of constrictor diameter (L/Ø = 0.5, G = 0.45 mm).

Fig. 21 Electric characteristics for 40 mg/sec mass flow as function of constrictor diameter (L/Ø = 0.5, G = 0.45 mm).

Fig. 22 Electric characteristics for 30 mg/sec mass flow as function of constrictor diameter (L/Ø = 0.5, G = 0.45 mm).
Fig. 23 Electric characteristics for 30 mg/sec mass flow as function of electrode gap.

Fig. 24 Electric characteristics for 50 mg/sec mass flow as function of electrode gap.

Fig. 25 Specific impulse vs. specific power as function of electrode gap (\( \phi = 0.5 \text{ mm}, \ L/\phi = 0.5 \)).

Fig. 26 Efficiency vs. specific power as function of electrode gap (\( \phi = 0.5 \text{ mm}, \ L/\phi = 0.5 \)).

Fig. 27 Constrictor section viewed from nozzle side after 10 h of functioning (\( \phi = 0.5 \text{ mm}, \ L/\phi = 1 \)), magnify ~ 40x.

Fig. 28 Constrictor section viewed from nozzle side after 10 h of functioning (\( \phi = 0.5 \text{ mm}, \ L/\phi = 2 \)), magnify ~ 38x.
Fig. 29 Constrictor section viewed from nozzle side after 10 h of functioning (\( \Theta = 0.7 \) mm, \( L/\Theta = 2 \)), magnificate \( \approx 38x \).

Fig. 30 Comparison of the specific impulse for coated and uncoated nozzle (\( \Theta = 0.5 \) mm, \( L/\Theta = 2 \), Gap = 0.45 mm).

Fig. 31 Comparison of the efficiency for coated and uncoated nozzle (\( \Theta = 0.5 \) mm, \( L/\Theta = 2 \), Gap = 0.45 mm).

Fig. 32 DAS samples of arcjet operational paremeters (\( \Theta = 0.7 \) mm, \( L/\Theta = 2 \), Gap = 0.45 mm).

Fig. 33 DAS samples of arcjet operational paremeters (\( \Theta = 0.7 \) mm, \( L/\Theta = 2 \), Gap = 0.45 mm).

Fig. 34 DAS samples of arcjet operational paremeters (\( \Theta = 0.5 \) mm, \( L/\Theta = 2 \), Gap = 0.45 mm).
Fig. 35 DAS samples of arcjet operational parameters ($\varnothing = 0.5$ mm, $L/\varnothing = 2$, Gap = 0.45 mm).

Fig. 36 DAS samples of arcjet operational parameters ($\varnothing = 0.5$ mm, $L/\varnothing = 2$, Gap = 0.45 mm).

Fig. 37 DAS samples of arcjet operational parameters ($\varnothing = 0.5$ mm, $L/\varnothing = 1$, Gap = 1.0 mm).

Fig. 38 Feedline and plenum chamber pressures for 40 and 50 mg/s mass flow rate ($\varnothing = 0.9$, $L/\varnothing = 1$, Gap = 0.4).

Fig. 39 Arc current transients registered for three typical energization level with the PCU power stage disconnected.

Fig. 40 Current start-up transient.
Fig. 41  Startup transient.

Fig. 42  Startup transient.

Fig. 43  Transient arc current for a typical startup (I = 10 A, \( m = 30 \text{ mg/s} \)).