Performance of Hot Cathode MPD Thrusters

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Experimental activities on pulsed MPD thrusters with an artificially heated cathode are presently underway at CENTROSPAZIO. These activities, initiated in the framework of an ESA ASTP3 programme, were primarily intended to simulate the continuous operation of multi-MW gas-fed thrusters more accurately, through laboratory tests in a pulsed (1 ms), quasi-steady regime. Moreover, recent mission studies have illustrated the advantages that may be drawn from the use of heated-cathode pulsed MPD thrusters for medium term applications, operating at an average power level of tens of kW. In these cases, the main aim of the cathode heating is to reduce cathode erosion, thus prolonging thruster life. Test results gathered to date on the heated-cathode thruster, reveal a more stable operation and a decrease in arc voltage drop with respect to a cold-cathode operation, even if thermionic emission is not significant. Thrust measurements have shown that cathode heating has no significant effect on the acceleration processes, confirming a quadratic dependence of the thrust on the current, in electromagnetic regime, and only marginal variations of the electromagnetic coefficient \( b \) from a cold to a hot cathode operation. Improvements have been made to the test set-up to allow testing to be performed more systematically and the characterization of different thruster configurations in the framework of follow-on experimental activities.

Nomenclature

\[
\begin{align*}
\text{b} & = \text{electromagnetic thrust coefficient, N/A}^2 \\
\eta_i & = \text{thrust efficiency} \\
I & = \text{current, A} \\
I_p & = \text{specific impulse, s} \\
I_i & = \text{full ionization current, A} \\
m & = \text{mass flow rate, kg/s} \\
T & = \text{thrust, N} \\
V & = \text{voltage, V} \\
\xi & = \text{dimensionless current (I/I_i)}
\end{align*}
\]

Introduction

As recognized from the considerable activity carried out on this matter in various laboratories \(^1\),\(^2\), the thermal condition of the cathode of an MPD thruster has a considerable effect on the current emission. Indeed a strong erosive extraction is typical in cold-cathode operation, while in heated-cathode operation a thermionic current emission takes place, drastically reducing the electrode erosion rate. In addition, an improvement in thruster performance is observed in heated-cathode operation with respect to a cold operation, due to a lower arc voltage drop. Nevertheless, the most significant advantage to be drawn from cathode heating is the considerable decrease in the erosion rate which directly implies prolonging thruster life. Indeed, due to its position in the discharge chamber and its limited dimension, the cathode seems to be the most critical component of the thruster as regards erosion.

Cathode temperatures at which a significant thermionic emission of current takes place, are typical of a steady regime of an MPD thruster operating in a continuous mode. On the contrary, a cold cathode operation with a high erosion rate may occur in a steady thruster during the start-up transient, or in a pulsed thruster, especially if it is operated with a low duty cycle. This latter case, in particular, is typical of quasi-steady multi-MW thrusters currently tested in many laboratories to simulate a continuous operation. In these cases, more realistic conditions can be achieved by artificially heating the cathode until thermionic temperature is reached.

In addition, recent studies have shown the advantages that may be obtained from cathode heating for the medium term application of MPD thrusters in space \(^4\). Pulsed MPD devices, operating with an average power level of tens of kW, seem to provide a more attractive performance than other propulsion options, despite the complexity of a pulsed system, as long as a thrust efficiency better than 50\% and a low erosion rate are exhibited. To this purpose, the heating of the cathode with a few hundred Watts during the initial phase of thruster operation is shown to be both compatible with the power availability and

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convenient in prolonging thruster life and increasing thrust efficiency.

With the objective of a more accurate simulation of a continuous, multi-MW operation of an MPD thruster (long term) as well as of the development of a pulsed, 10-30 kW device (medium term), CENTROSPAZIO is currently involved in an experimental activity on MPD thrusters with cathode heating, in the framework of an ESA programme. After the promising results of a series of preliminary tests, improvements were made to the experimental apparatus and the test equipment, as described in the following. In addition, some of the most significant results gathered are illustrated in the paper.

Experimental Apparatus

As shown in Fig. 1, the MPD thruster with cathode heating developed at CENTROSPAZIO has a ring anode configuration, a copper anode with an inner diameter of 100 mm and an anode-to-cathode radius ratio of 5. The cathode heater consists of a 2% thoriated tungsten stick placed inside a hollow cathode, with its sharp conical edge a few mm from the bottom. This is specially shaped to facilitate activation of an electrical arc between the two electrodes. The cathode, made of 2% thoriated tungsten, has the usual cylindrical surface and hemispherical edge. This surface is heated by the electric arc ignited between the cathode and the inner electrode. Two cathode lengths are currently available: a short one, for which experimental results have been gathered, and a longer one, with its tip extending to the external anode surface. The latter configuration was adopted to investigate a thruster with a large heated-cathode surface. In addition, another externally-identical cathode was manufactured without the cathode heater, in order to compare the external surface of geometrically similar cathodes operating with and without cathode heating, after an appropriate number of firings had been performed on both of them.

All of the insulators are made of boron nitride, except the heater stick insulator, which is made of alumina. Gas can be injected separately into the discharge chamber through an annular orifice at the cathode root, and/or towards the anode, by means of twelve orifices drilled on the boron nitride backplate.
Test Equipment

The baseline test equipment used for this activity is the same as that adopted for testing on MPD thrusters at CENTROSPAZIO\textsuperscript{34}, although important modifications were made in order to perform the cathode-heating activity safely, as illustrated in the following. The experimental set-up is based on a fibreglass vacuum chamber equipped with a diffusion pump capable of an ultimate pressure of about $4 \times 10^{-4}$ mbar before each firing. The anode and cathode gas injection is supplied by a gas feeding system consisting of a solenoid valve and a reservoir for each line. The valves produce gas pulses of about 50 ms with a long plateau during which a steady mass flow rate is maintained. Moreover, the system consists of a series of pressure tanks and reducers which allow the management of different gases and mixtures for the anode and cathode injections (Figs. 2 and 3).

A Pulse Forming Network supplies quasi-steady, current pulses of 1 ms in duration and a maximum discharge current of about 30 kA. The discharge is activated by an ignitron. In order to perform the firing when a steady mass flow into the thruster is reached, this ignitron is delayed with respect to the opening of the valves. The duration of this delay was determined by a preliminary mass flow calibration, following the same procedure used for a previously-developed thruster family\textsuperscript{5,9}.

The electric arc of the cathode heater is ignited and fed by a TIG welding unit (Cetass CM 520) consisting of a high frequency igniter connected to a DC power supply. The temperature of the cathode tip is measured with an optical fiber pyrometer (ACCUFIBER mod 900 PY HF) which is placed in front of the cathode by means of a pendulum moved by a synchronous motor. The pendulum allows the pyrometer to be placed in a safe position when the desired cathode temperature is reached, just before firing. A typical test procedure involves the following main operations:

- pyrometer positioning for cathode temperature measurement;
- heater arc ignition;
- PFN charging;
- when the desired cathode temperature and PFN charging voltage are reached:
  - pyrometer positioning in a safe site;
  - heater arc extinguishment;
  - firing.

In order to facilitate the performance of this test procedure a Programmable Logic Controller (PLC, General Electric) which can be driven by a control panel and/or a computer (Macintosh IIvx) was adopted, as illustrated in Fig. 4.

The equipment used to measure the electrical characteristics consists of two high voltage probes (Tek P615 1000X), an operational amplifier (Tek AM501) for arc voltage drop measurement and a Rogoswski coil, passively integrated for total current measurement. Thrust measurements were carried out with a virtual hinge thrust stand, using the ballistic method, described in the next section\textsuperscript{5}. A proximity transducer (Bently Nevada mod 7200), was used to measure the motion of the mobile mass of the thrust stand just after firing.

The signals were gathered by a transient recorder HP 5185 and then transferred to the computer (Macintosh IIvx) for data analysis and storage. The computer is the same one as that used for the test procedure management (Fig. 4).

![Fig. 2 The thruster on the flange](image-url)
Fig. 3 The gas feeding system

Lock Switch
Reservoir Pressure
Safety Switch
Discharge Switch

Control Panel
Test Procedure Activation
Heater Current Level
PFN Charging Voltage
Test Procedure Status

Programmable
Logic Control
Pyrometer Positioning
Cathode Heater Ignition
Cathode Temperature Control
PFN Charge
Contactor Operation

Solenoid Valve Activation
Ignitron Control System Activation

Transient Recorder
HP 5185
Measurement Set-up
Signals
Signals from Diagnostic Devices

Test Procedure Status
Heater Current Level
PFN Charging Voltage

Test Results
Graphs and Tables
Analysis Results

Fig. 4 Test automation and data acquisition system arrangement
Experimental Results

The test results described in the following refer to the experimental activity carried out in the framework of the ASTP 3 programme. The experimental apparatus and the test equipment adopted for this activity is the same as that described in ref. 7. Results on the improved thruster and the experimental set-up described above are not yet available and will be presented in subsequent papers.

Preliminary test results. In preliminary tests carried out for the measurement of the electrical characteristics at 4 g/s a remarkable difference was observed between operation with cathode heating and operation without (Fig. 5). A net reduction of the arc voltage drop and electromagnetic noise on the voltage signal was observed with cathode heating when compared to cold electrode operation 7. However, when such tests were repeated in a new series of experiments, these results were not reproduced (Fig. 6).

The cause of this is not yet completely clear. A fault on a boron nitride insulator between anode and cathode was discovered during further cold cathode tests. This failure was probably due to the numerous thermal cycles to which the various components of the thruster were subjected during testing, finally resulting in the cracking of the insulator. As a consequence, a short circuit was observed between the electrodes at PFN charging voltages above 600 V. In fact, when the PFN charging voltage was increased, a sharp decrease in arc voltage drop was observed, as only a fraction of the current flowed through the arc, while a considerable amount flowed through the short circuit. This could explain, at least to some extent, the irregularity of the results gathered during the preliminary tests. Indeed, the electrical characteristic without cathode heating, measured after that with cathode heating, is similar to other ones measured on other thrusters and did not suffer the short circuit effects. Most probably, due to dilation of the thruster body during testing with the cathode heating, the fracture on the faulty boron nitride insulator cracked opened, thus causing a short circuit. During cold operation, on the other hand, these fractures remained closed, until further deterioration occurred during subsequent cold tests.

As a consequence, a series of modifications were made to the thruster design in order to avoid a repetition of this kind of failure. Moreover, a series of preliminary checks, aimed at verifying the proper insulation of the electrodes, were included in the test procedure. In particular, both before and after a series of tests, the external cathode surface is insulated with mylar and, when the vacuum condition is reached, a voltage up to 3000 V is applied between the electrodes by a limited-current power supply. If no current flow is observed before testing, test procedure is continued, if no current flow is detected after testing, test results are considered as properly gathered. In the reverse case, tests are not performed or are rejected.

Electrical Characteristics. Tests were carried out to measure electrical characteristics at 1, 2 and 4 g/s of Argon with and without cathode heating. The most investigated mass flow rate was 4 g/s. The electrical characteristics with cathode heating were performed with a cathode tip temperature of about 2300 K, measured by the pyrometer during a preliminary cathode heating calibration. Electrical characteristics were measured following different test procedures (measurement of the characteristics with cathode heating soon after the measurement without cathode heating and vice versa; measurement of the characteristics in different days) and no significant variations were observed. In Fig. 6 the characteristics at 4 g/s are compared. Each data point was obtained as an average of three voltage-current values taken at 0.5 ms from the start of three firings performed at the same PFN charging voltage. The electrical characteristics with cathode heating exhibit a lower arc voltage drop for the entire current range. A decrease in voltage was also observed at 1 and 2 g/s. Fig. 7 shows an electrical characteristic comparison at 1 g/s. Here a larger voltage decrease with cathode heating can be noticed. Electrical characteristics at 2 g/s are not reported as they did not exhibit a good reproducibility, even if the same general behaviour was also observed for this mass flow. A voltage signal comparison was also carried out for the two cathode thermal conditions at 4 g/s, as illustrated in Figs. 8 and 9. These signals were gathered after a firing with cold electrodes and soon after another firing with a cathode temperature of 2300 K, at the same PFN charging voltage. The voltage signal with cathode heating is lower, more regular and with reduced electromagnetic noises with respect to the signal taken without cathode heating.

Mass Flow Check. A possible explanation of the improvement in electrical characteristics (and, as a consequence, performance) due to cathode heating may be the availability of a larger mass flow with respect to the one determined on the basis of the mass flow calibration, carried out with cold electrodes. A regular extra flow corresponding to about 0.3-0.4 g/s of Argon could, in part, explain the improvement in the electrical characteristics. During a correct operation of the heater, no significant increase in vacuum chamber back pressure was observed (back pressure range from 4 to 8 x 10^(-3) mbar). The
extra mass could thus be supplied directly from the gas feeding system, or eroded from the electrodes or the insulators in the acceleration chamber, during firing. A series of verifications were made to this purpose. As regards a possible gas feeding system contribution, the mass injected for each gas pulse was measured both with and without cathode heating for a nominal mass flow of 4 g/s using a mass flow meter (Micro Motion® mod. D6). The mass flow meter was placed behind the solenoid valve on the gas line. Further tests were performed measuring the vacuum chamber pressure increase due to the gas pulse. These tests showed that there are no variations in total mass injected when operating with or without cathode heating, and thus no variation in mass flow can be reasonably extrapolated. Very thorough tests would imply the performance of the entire mass flow calibration procedure with cathode heating. However, these tests are very complicated, and should only be carried out if future total mass measurements give doubtful results. On the other hand, the effects of a temperature increase of the gas feeding system in the thruster body (up to 300°C, as measured with thermocouple) are marginal and conflicting (increasing effect: choking orifice dilatation, irrelevant considering the low thermal expansion of the HP Boron Nitride, decreasing effect: heating of the gas flow).

A greater erosion of the thruster component during heated-cathode operation was not evident upon visual observation of the thruster after testing. However, the thruster has performed relatively few shots, and thus accurate conclusions on thruster erosion cannot be drawn. On the contrary, a reduced cathode erosion was qualitatively observed after a series of tests with cathode heating, with respect to a similar cathode used for approximately the same number of shots, during testing on a thruster family. In conclusion, the observed improvement of the electrical characteristics does not seem to be due to any spurious additional mass.

**Thrust Measurements.** Thrust measurements were carried out with a ballistic method. The total impulse of the thrust is determined measuring the displacement of the mobile mass of the virtual hinge thrust stand, on which the thruster is fixed, soon after the shot, with the proximity transducer. The relevant arc current is simultaneously measured, and an instantaneous thrust value is obtained assuming that the acceleration process be purely electromagnetic, and thus the thrust expression is the following:

\[
T = bI^2 \quad \text{for } I > I_\text{fi} \\
T = bI_\text{fi} \quad \text{for } I \leq I_\text{fi}
\]  

Fig. 5 Preliminary Results (4 g/s)

![Graph](https://via.placeholder.com/150)

Fig. 6 Electrical characteristics at 4 g/s

![Graph](https://via.placeholder.com/150)

Fig. 7 Electrical characteristics at 1 g/s
The effective mobile mass was previously determined by a thrust stand calibration\(^6\). During testing with cathode heating, the possible variation of the dynamic characteristics of the stand was verified, measuring its natural frequency of oscillation during testing. No significant frequency variations were observed. Nevertheless, thrust stand calibration was repeated during the activity. A cold gas contribution must be subtracted from the total impulse to obtain the one relevant to the thrust. This contribution was previously measured for the mass flow rates tested with and without cathode heating. A considerable increase in cold gas impulse was observed in heated-cathode operation. This sort of "resistojet effect" depends on the heating and then the expansion of the gas injected around the cathode at incandescent temperatures.

In Fig. 10 a comparison between cold and hot cathode operation is illustrated. Each point is an average of three measurements carried out at the same PFN charging voltage and all of the data are relevant to the electromagnetic regime (\(\xi > 1\)). Considering the precision of such a measurement, cathode thermal condition does not seem to have a significant effect on thrust. The b value for a cold cathode is \(2.48 \times 10^{-7}\), while for hot cathode it is \(2.33 \times 10^{-7}\) (about 6\% less), fitting data with a curve like:

\[
T = b I^2 \quad \text{(3)}
\]

The quadratic dependence of the thrust, with respect to the current and the b values found, is in good agreement with results obtained on similar thrusters\(^4,5\). The slightly lower b value with a hot cathode could be explained by a lower cathode erosion rate at high cathode temperature and thus a minor contribution to the thrust from the eroded material.
Discussion. The cathode temperature at which tests with cathode heating were performed (2300 K) permits the thermionic emission of a small fraction of the entire arc current. A large thermionic emission requires operation at higher cathode temperatures (beyond 3000 K), or the adoption of a different tungsten alloy from thoriated tungsten, with a lower work function. The improvement observed in thruster performance could be explained by a more regular and diffused current emission from the cathode. This implies a cathode erosion decrease, and a more symmetric and stable arc for the entire pulse duration, with respect to a cold cathode operation. The larger voltage reduction observed at 1 g/s with respect to 4 g/s could be explained by assuming that the improvement due to cathode heating is focused in the cathode region in particular, and that the effect is a substantial reduction of the cathode voltage drop. If the cathode sheath is assumed to obey Child’s law, the cathode voltage drop is larger at lower mass flow rates than at higher ones, at the same nondimensional current level, as shown in the expression:

\[ V_{\text{sheath}} = \text{const.} \frac{2}{3} \left( \frac{V}{m} \right) \]

Thus, the cathode voltage to arc voltage drop ratio, is generally higher at lower mass flow rates. As a consequence, if the cathode heating is assumed to reduce that fraction of the arc voltage significantly, this effect should be more evident at lower mass flow rates than at higher ones. Although this explanation is consistent with the results gathered, it needs further experimental confirmation, especially from plasma diagnostics close to the electrodes.

Performance Comparison. Electrical characteristic and thrust measurements permit the evaluation of thruster performance. Specific impulse and thrust efficiency was calculated at 4 g/s of Argon for cold and hot cathode conditions on the basis of the following expressions:

\[ I_s = \frac{T}{mg} \]

\[ \eta_T = \frac{T^2}{2 m V I} \]

In Fig. 11 the performance are compared. A decrease in thrust efficiency occurs close to the full ionization condition, as observed in similar thrusters. Nevertheless, an increase in thrust efficiency with cathode heating can be observed for the entire range of currents investigated (from 20 to 10% of the cold cathode value).

Conclusions

Experimental activity on MPD thrusters with cathode heating is in progress at CENTROSPAZIO. Tests carried out to date have shown that cathode heating has no marginal effect on the operation of a pulsed, multi-MW MPD thruster. Operation at high cathode temperatures seems to yield a reduction in cathode erosion and the improvement of thruster performance, even if thermionic emission is not significant. Cathode heating seems to be critical not only in simulating a continuous operation, but also in improving the performance and life of pulsed thrusters.

Results gathered have shown that cathode heating decreases the arc voltage drop and seems to have no significant effect on the thrust with respect to cold-cathode operation. More accurate tests, including plasma diagnostics, will be carried out to confirm these results and to find the physical reasons of cathode heating effects. To this purpose, the experimental apparatus and test equipment available at CENTROSPAZIO are being improved, in order to perform more systematic tests which will include additional thruster configurations.
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