Experimental Study of FEEP Emitter Starting Characteristics

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Field Emission Electric Propulsion (FEEP), which has undergone extensive research in Europe over the past eighteen years, now represents one of the most interesting alternatives to the traditional propulsion technologies for low-thrust applications. Its characteristics of high specific impulse, accurate thrust control both in stationary and pulsed mode, and intrinsic structural simplicity make the FEEP system a very attractive concept, even taking into account problems arising from the utilization of caesium as a propellant and the high specific power levels required. The present paper describes the experimental facility presently available at Centrospazio and outlines the programmes being carried out in the FEEP area. The results of a first series of tests, aimed at the investigation of the quality of emission as a function of background pressure, are presented and discussed. The complete electrical characterization of the emitter has been made for three different pressure levels, together with a one-hour duration test. The analysis of the data collected enables to evaluate the variation of the beam current during the initial phase, showing a strong dependence upon the evolution of the degree of wetting of the emitter blades by the propellant. The concept of emitter ageing is introduced, as a fundamental phase of the pre-flight preparation procedure. Further experimental test activities are envisaged.

Introduction

The interest in development of field emission thrusters stems from a certain number of advantages this system offers with respect to other propulsive concepts at the same thrust level. FEEP emitters may be regarded as second generation electrostatic thrusters: ion production occurs from liquid phase, thus avoiding thermal losses for propellant vaporization. The efficiency of conversion of electric power to propulsive power reaches values as high as 98%, versus a maximum 80% of other ion engines; specific impulse is in the range of 6000+10000 s, and may be easily adjusted to meet specific mission requirements. Thrust level is finely tunable, and instantaneous switching capability allows pulsed mode operation. Clusters of emitters have been successfully tested. The problems involved with the high specific power (40+60 W/ mN) could be easily overcome in future NEP (Nuclear Electric Propulsion) systems, while new caesium storage systems, designed for safety and reliability of operation, are under development.

FEEP research has been carried out by ESA since 1972; the thruster has evolved from a single pin configuration, to arrays of stacked needles, to the present linear slit emitter. During the previous phases of the development programme all the components of the system were designed and tested, and the emitter manufacture problems solved. Development has now entered the industrialization phase, and present research is devoted to the testing of the whole system in view of a flight experiment.

FEEP activities in Italy, formerly carried out at the Department of Aerospace Engineering of the University of Pisa, have been moved to CENTROSPAZIO, a new space technology laboratory set up in 1989 as a part of the Pisa Research Consortium. A contract has been awarded by ESA to the french Société Européenne de Propulsion (SEP), with CENTROSPAZIO acting as a subcontractor.

The underlying physical principle in FEEP thrusters is the so-called field effect. Liquid Metal Ion Sources (LMIS) based on this principle have been widely used in technology, physics and chemistry for years. Under a strong electric field the free surface of a liquid metal distorts itself, creating a series of protruding cusps; the local electric field on the tip becomes larger and larger as the radius of curvature of the cusps becomes smaller and smaller. When the electric field approaches a value of about 10^9 V/m the atoms of the tip ionize and...
are extracted by the same electric field, while the electrons are rejected in the bulk of the liquid; no transitional vapour phase is required. The radius of curvature of the free metal surface is typically in the order of 1 μm, hence an applied voltage of about 10 kV is sufficient to obtain the necessary field. The particles extracted are replaced by the hydrodynamic flow.

The FEEP system consists of emitter(s), accelerator electrode, neutralizer, propellant feeding system and power conditioning and control unit.

The solid slit emitter is schematically represented in fig. 1 and fig. 2. The emitter halves are separated by a thin sputter-deposited Ni layer; when clamped together, the halves form a narrow slit, of elongated elliptical, near rectangular shape. The body of the emitter module forms a small propellant reservoir. The main configuration parameters are the emitter length and the slit height. The accelerator consists of a simple metallic plate with a rectangular hole facing the emitter slit. The main parameter of interest is the distance between the two electrodes, a typical value being 0.6 mm.

Aim of the study

Past experience on FEEP emitters has shown that the start up phase is the most critical in the operation of the thruster. During this phase, problems may arise from the first wetting of the surfaces of the emitter blades by the propellant. A proper wetting is of paramount importance in order to obtain a high-quality emission, i.e. a homogeneous distribution of emission sites along the slit length. Other problems may be caused by impurities and/or oxidation. Caesium is rapidly oxidized by air and reacts very quickly with water; caesium oxide deposits on the emitter edges may obstruct the slit, dramatically reducing or preventing the emission. Even excessive wetting, due to dust particles or damaged slit edges, may cause problems, allowing the propellant to wet the outer surfaces of the tips, thus causing sparking.

The wetting behavior of emitters depends mainly on three factors:

- emitter material;
- outgassing procedure (must ensure the complete removal of water vapour);
- slit height.

At present, best results in terms of wetting characteristics and mechanical properties are offered by Inconel X 750 (a Ni alloy with 14 + 17% Cr).

The outgassing procedure consists of baking out the emitter at a high temperature, under very high vacuum, for a certain duration. In laboratory tests, very high temperatures can be obtained, while a minimum bakeout temperature must be selected for a flight model.

The mass efficiency of the thruster, defined as the ratio of charged particles to the total mass flowing, is proportional to the reciprocal of the third power of the slit height. The limit value compatible with technological feasibility is about 1.2 μm, but a slight increase of this value to about 1.8 μm is possible, allowing for a strong reduction in hydrodynamic impedance (by a factor 3.5) without unacceptable mass efficiency decrease, thus easing the flow of propellant towards the slit edges.

Wetting problems are most likely to be encountered the first time the emitter is fired; subsequent firings are much easier. Thus, it has to be decided whether the outgassing must be done at ground or in orbit. The first solution implies storing the emitter under vacuum after an acceptance firing test; the second solution requires a complete cleaning of the emitter to be carried out after the acceptance test.

In order to select the pre-flight preparation procedure a series of tests has been planned. The behavior at starting will be investigated as a function of the following parameters:

- the slit height (two values: 1.2 μm and 1.8 μm);
- the baking temperature (three values: 250 °C, 350 °C, 450 °C);
- the background pressure (three values: 3 x 10^-5 mbar, 5 x 10^-5 mbar, 1 x 10^-4 mbar).

The final objective of the tests is to define the appropriate baking temperature at each pressure level for both emitters, for a total of 18 tests. Bakeout duration is assumed to be approxi-
mately 15 hours (one night). As a subcontractor of SEP, CENTROSPAZIO is responsible for the conduction of the experimental activities. Until now the first 3 tests have been performed; results are presented in the following.

The experimental setup

CENTROSPAZIO is equipped with three vacuum facilities. Tests on field emission thrusters are carried out in IV1, the smallest of the three, capable of the highest level of vacuum.

The main chamber of IV1 vacuum plant consists of a cylindrical stainless steel vessel, approximately 1 m long and 0.6 m in diameter, with a volume of 0.3 m³. On the front end of the main chamber is the test chamber, with a inner diameter of 340 mm and a length of 380 mm, equipped with the experimental flange, which bears the emitter-accelerator assembly, the propellant feeding system, two emitter heaters made of tungsten wire, and thermocouples for the monitoring of temperature. An airlock, equipped with an emitter manual positioning system, is mounted on one side of the test chamber.

The main chamber is equipped with a rotary vane pump and a cryopump, with a pumping speed of 800 l/s; the airlock is equipped with a turbomolecular pump, backed by a rotary vane pump. The ultimate pressure of the vacuum plant is in the range of $10^{-6}$—$10^{-8}$ mbar. The facility is equipped with a complete set of pressure gauges and a quadrupole mass spectrometer. A set of low and high voltage power supplies, gaseous feeding lines and general laboratory instrumentation is available.

The propellant feeding system consists of a glass siphon containing a sealed ampoule filled with 2.5 g of caesium. The actuation of a small electromagnetic gun breaks the seal of the ampoule; caesium is then forced into the terminal capillary by means of a slight overpressure of spectroscopically pure argon. Caesium droplets fall into a small funnel, connected with the emitter reservoir. Overpressure is released when visual observation shows that enough caesium (some droplets) has reached the funnel. The temperature of the system is controlled by means of a filament heater and a thermocouple, in order to keep the propellant above its melting point (28.4 °C).

In view of future tests in pulsed mode, a dedicated Experimental Emitter Pulse Unit has been provided by ESTEC. The pulsed mode instrumentation is completed by a word generator (HP8006A) and a digitizing oscilloscope (HP54501A).

Test report

The tests performed were devoted to studying the influence of ambient pressure. The following points were investigated:

- the value of $\Delta V_{on} = V_e - V_a$ at the start of emission (onset voltage);
- the evolution of $I_e$ once fixed the voltage at the electrodes, on the period of one hour (wetting progress);
- the characteristic curve, $I_e = f(\Delta V_{on})$.

An Inconel emitter with a slit length of 5 cm and a slit height of 1.8 µm has been tested. The emitter was received new from ESTEC.

The outgassing procedure was accomplished by heating the emitter with a tungsten filament. The emitter was connected to a power supply, raising its potential to +410 V with respect to ground, in order to attract the electrons released from the filament, thus concentrating the thermal power on the surfaces to bake out. The emitter temperature was maintained at about 450 °C for 15 hours, then the emitter was left cooling down. Spectrometrical analysis of the composition of the residual atmosphere, respectively before and after the bakeout, show a drastic reduction of partial pressure of water vapour. A prolonged, high temperature bakeout can help in the elimination of the vapours adsorbed on the metallic surfaces; on the other hand, it could induce severe local stresses in blade tips causing deformation, thus resulting in unpredictable perturbations of propellant flow. Optimization of duration and temperature of bakeout will be pursued in a future series of tests.

After the propellant filling, the emitter was maintained at a temperature of about 40 °C, high enough to avoid propellant solidification and low enough to prevent excessive evaporation, and electrostatic checks were made. As soon as the first pressure level selected ($3 \times 10^{-4}$ mbar) was reached, the accelerator electrode voltage was set to -5 kV, in order to create a potential barrier for shielding the emitter from secondary electron bombardment. Positive voltage was then applied to the emitter and a regular emission was initiated.

The duration test was performed setting the electrode voltages to values corresponding to a 2 mA emission; during the next hour, the emitter and accelerator currents were recorded in steps of 2 min, the electrodes polarization remaining unchanged. At the end of the test, the chamber pressure had raised to the value of 8.2 $10^{-7}$ mbar. As soon as the test pressure was resumed, the characteristic curve ($I_e$ versus $\Delta V_{on}$) was recorded. Tests were conducted at constant $V_e$, varying $V_a$ in steps of 500 V; at $\Delta V_{on} = 14$ kV some sparking occurred, probably due to the presence of caesium vapours in the near of the electrodes. At the end of characteristic recording chamber pressure was 3.4 $10^{-4}$ mbar.

The next two tests were performed in a similar manner; pressure was regulated by throttling the gate valve between the cryopump and the main chamber.

At the end of the three tests a certain amount of caesium was still in the emitter reservoir; it was then decided to run a fourth test, not foreseen in the schedule, to investigate the behavior of the emission at a relatively high pressure ($3 \times 10^{-7}$ mbar).
Analysis of experimental data

The following quantities were recorded:

- emitter current, \( I_e \);
- accelerator current, \( I_a \);
- chamber pressure, \( P_{ch} \);
- emitter temperature, \( T_e \).

Thrust and mass flow were computed theoretically. Specific impulse and specific power are functions of the emitter voltage only; at \( V_e = 5 \) kV their actual values are:

\[
I_w = 8650 \text{ s} \\
P_{wp} = 42.5 \text{ W/mN}
\]

Test no. 1 (\( P_{ch} = 3 \times 10^4 \text{ mbar} \))

The emission current \( I_e = 2.0 \) mA was first obtained at:

\[
V_e = +5.0 \text{ kV} \\
V_a = -5.5 \text{ kV}
\]

During the first 12 min \( I_e \) increased up to \( 3.0 \) mA (fig. 3), from the 12th to the 32nd minute the increase was 0.3 mA only; from the 32nd minute onwards, the emitter current reached its final value, very close to the corresponding value on the characteristic. The absolute value of \( I_e \) increases with time, but the ratio \( I/I_e \) decreases from an initial 7% to about 5%; this denotes the decrease of beam divergence as the slit wetting percentage increases and emission becomes smoother. During the test the temperature of the emitter raised from 42 °C to 45 °C, without heat input from the heaters; this is probably due to the impact of a certain number of free electrons that have enough energy to overcome the accelerator electrostatic barrier. Fluctuations in measured values are to ascribe to the gradual assessment of emission, due to the irregular development of wetting and to the removal of impurities from the blades.

Fig. 4 - Accelerator current

Fig. 5 - Current ratio

Fig. 6 - Emission current

Fig. 7 - Accelerator current
The onset voltage was defined, conventionally, as the $\Delta V_{\text{onset}}$ corresponding to the lowest emission current detectable by the experimental apparatus (0.1 mA); its value was (fig. 6, 7):

$$\Delta V_{\text{onset}} = 8.0 \text{ kV}$$

The initial and final slopes of the characteristic were

$$\frac{dI}{dV_w} = 0.45 \text{ mA/kV}$$
$$\frac{dI}{dV_w} = 3.8 \text{ mA/kV}$$

Electrical efficiency, defined as the ratio between the power carried by the ion beam and the electric power input, is always above 90%.

**Test n. 2 (Pch = $5 \times 10^{-8}$ mbar)**

The difference of potential needed for the 2 mA emission was:

$$\Delta V_{\text{tot}} = 10.38 \text{ kV}.$$
was reached within an hour (fig. 13, 14). Finally, the percentage value of $I_e$ is lower than in previous cases (3.2%); this can be regarded as an index of a more regular space distribution of the emission sites.

The onset voltage was:

$$\Delta V_{\text{onset}} = 8.23 \text{ kV}$$

This value further confirms the constant increasing of the slit wetting; the slopes of the characteristics (fig. 16, 17) are:

$$\frac{dI_e}{dV_{\text{onset}}} = 0.37 \text{ mA/kV}$$

$$\frac{dI_e}{dV_{\text{onset}'}} = 4.0 \text{ mA/kV}$$

Test n. 4 ($P_{ch} = 3 \times 10^{-7} \text{ mbar}$)

The effects of the higher pressure are evident:

- increase of the onset voltage (9.5 kV);
- decrease of $I_e$, at the same voltage;
- high values of $I_e$;
- low electrical efficiency (between 0.76 and 0.89).

The curves (fig. 18, 19) were recorded three days later than the previous ones; the deterioration in performance could be caused, partially, by the formation of caesium oxides on the slit.
An experimental facility for field emission electrostatic thruster testing has been set up and successfully operated at CENTROSPAZIO. A series of tests has been conducted as the first step of a complete investigation programme on the starting performance characteristics of FEEP emitters, within the framework of the ESA Field Emission Electric Propulsion Programme. Experimental results show the dependence of initial wetting and emission quality upon background pressure.

Plans for future activities include the completion of wetting tests and the selection of a detailed emitter pre-flight preparation procedure; pulsed mode tests will be performed in parallel in early 1992.

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References


