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Performance and lifetime testing of a pulsed plasma thruster for Cubesat applications

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ABSTRACT

This paper describes the design and testing of the engineering model of a pulsed plasma thruster for Cubesat applications (PPTCUP-EM). It has been developed by Mars Space Ltd, Clyde Space Ltd and the University of Southampton with the main aim of increasing the in-orbit lifetime of Cubesats by providing drag compensation. Nevertheless, this thruster can be also utilized to perform formation flying, small orbit changes and Cubesat end of life deorbiting. A test campaign has been carried out to prove that the thruster and the conditioning electronics lifetimes are long enough to utilize all the propellant stored on-board. From the results of the test, the PPTCUP-EM can deliver a total impulse of 42.9 ± 3.9 N s in about 1,125,000 shots. Moreover during the test campaign, a total of more than 1,800,000 shots have been achieved providing a safety factor of about 60% with respect to the number of required shots. The results gathered, including a preliminary characterization of the electromagnetic noise generated by the unit, are presented and show that the overall thruster performance is not influenced by the thruster aging.

1. Introduction

Cubesats are a fast growing sector in the space industry, allowing for cheap and easy access to space. They are normally launched into sun-synchronous or LEO orbits with an altitude of about 600–650 km. However they are currently limited by their lack of orbit control and their lifetime is therefore determined by the natural drag-induced de-orbiting. Pulse Plasma Thrusters (PPTs) have been shown to be suitable for Cubesat applications, due to their high scalability in terms of geometry, power input and performance and relatively low cost. Developed in the late 60s, PPTs represent the first example of electric propulsion successfully employed in space with Zond-2 (USSR) and LES-6 (USA) being the first satellites to have used plasma thrusters [1]. From then on, PPTs have been designed and developed, focusing both on high or very high energy (up to 100 J) devices [2–5] and on low energy (less than 10 J) thrusters [6–10] that may be used for the orbital and/or attitude control of micro, nano and pico-satellites, i.e. Cubesat. At the time of writing, the endurance test performed on a Cubesat PPT with the longest lifetime is reported by Krejci et al. [8]. This PPT delivers a total impulse of 1.7 N s in about 420,000 shots with a shot energy of 1.82 J. This corresponds to a velocity change $\Delta v = 2.6$ m/s or 1.7 m/s respectively for a 2U and a 3U Cubesat.

Mars Space Ltd, Clyde Space Ltd and the University of Southampton successfully completed a research study funded by the ESA-ITI program producing a breadboard PPT model for Cubesat applications (PPTCUP-BB) [10]. This thruster has been designed to deliver a total impulse (I_T) in the range between 28.4 and 44.0 N s and to match the tight Cubesat mass and volume budgets. However, PPTCUP-BB was able to perform only a few thousands shots mainly because of failures occurring in the capacitor banks and short circuiting of the electrodes due to carbonization [11].

Starting from the PPTCUP-BB design, the PPTCUP engineering model (PPTCUP-EM) has been developed to achieve a thruster lifetime long enough to deliver a total impulse (I_T) of 44 N s. Such an impulse is enough to double the lifetime of a 2U Cubesat orbiting at 250 km and consequently increasing its economical and scientific attractiveness [12].

In this paper the design of the EM thruster and the experimental results of the lifetime campaign are reported. The campaign has been carried out to demonstrate the lifetime of the entire unit, consisting of the thruster and the conditioning electronics at the stage of engineering models. Moreover, the results of a preliminary characterization of the electromagnetic noise generated by the unit are reported. To the best knowledge of the authors, only a few papers in the PPT literature deal with the electromagnetic

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Nomenclature

a-C	amorphous carbon
BB	Breadboard Model
C	capacitance
E	initial energy
EDX	Energy Dispersive X-ray
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
f	fundamental frequency of the main discharge
GSE	Ground Support Equipment
HV	High Voltage
Ibit	impulse bit
Isp	specific impulse
I_T	total impulse
LV	Low Voltage
m_{bit}	mass bit consumption
M_{prop}	propellant mass
n_{shots}	number of shots
PPT	Pulsed Plasma Thruster
RMS	Root Mean Square
SEM	Scanning Electron Microscope
t	time
V_0	initial capacitor bank voltage
Δv	velocity change
α	propellant divergence angle
η_{th}	overall efficiency

noise produced by low energy PPTs ([13] and [14]), whereas most of the papers that treated electromagnetic noise present experimental measurements that refer to discharge energies about one order of magnitude higher than the one presented in this paper ([9,15,16] and references therein). For this reason, the results of test performed on the PPTCUP-EM may be used to improve the understanding of the electromagnetic noise production in low energy discharge PPTs.

2. Thruster design

In this section the thruster design will be briefly presented. The PPTCUP-BB configuration, which is described in detail in [10] and [17], has been used as a guideline for the updated thruster design. The overall dimensions of the discharge chamber have not been significantly changed in the updated design. The initial mass of the propellant (M_{prop}) is about 8 g. The propellant area exposed to the main discharge is about 0.0001 m^2. The whole test campaign has been performed at $E = 2.00 \pm 0.02$ J, which corresponds to an initial voltage $V_0 = 1720 \pm 10$ V. The spark plug, which is used to trigger the main discharge, operates with an initial energy of about 0.01 J and an applied voltage of 7.5 kV. As for the breadboard model, the PPTCUP-EM has a 1.6 μF capacitor bank, used to store the shot energy E. The bank consists of a parallel arrangement of 8 ceramic capacitors rated up to 2000 V and with a nominal capacitance $C = 200$ nF. These capacitors have been chosen after an extended test to prove their reliability when used for pulsed applications to avoid failures similar to those occurred during the PPTCUP-BB test campaign [11].

The new PPTCUP-EM design was aimed at reducing the carbonization phenomenon that is conventionally indicated as the main life limiting mechanism for PPTs [18–21] and one of the main issues found during the testing of PPTCUP-BB [11]. Its main effect is the deposition of a thin layer of amorphous carbon (a-C) on the discharge chamber walls (i.e. the lateral walls and the back plate) that could eventually create a conductive path between the two electrodes shorting the capacitor bank causing a definitive thruster failure.

Lateral grooves have been included on the lateral walls of the discharge chamber to prevent the electrodes short circuiting. Moreover, the electrodes and the divergence angle of the nozzle walls have been modified to create a gap between them so as to avoid direct contact, as shown in Fig. 1.

In addition to this the PPTCUP-EM design allows the spark plug to be located in two different slots inside the cathode to assess the influence of the spark position on the performances of the thruster. As shown in Fig. 1, the two slots are named “Close” and “Far” holes. The former is the closest to the capacitor bank, on the inner edge of the cathode; the latter is furthest from the capacitor bank.

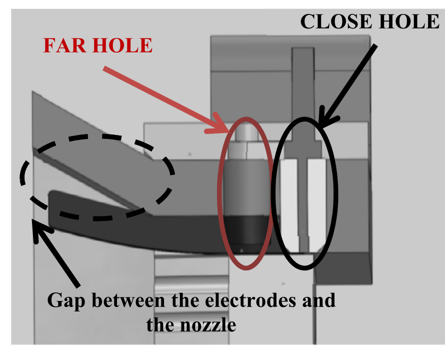

Fig. 1. 3D CAD of the two possible spark plug configurations.

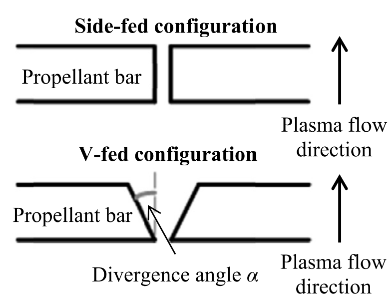

Fig. 2. Definition of side-fed and V-fed configurations.

In addition to the two possible positions of the spark plug, the unit was also tested in two different feeding configurations, i.e. the side-fed and the V-fed configurations, as shown in Fig. 2. The divergence angle α that characterizes the V-fed configuration has been fixed to 15°. The possibility of testing the thruster in different configurations allowed the acquisition of more data to prove the PPTCUP-EM lifetime and, at the same time, to optimize the thruster performances.

3. Experimental apparatus

3.1. Test sequence

The PPTCUP-EM test campaign was divided in two phases. In the first one, the thruster was tested using a dedicated ground support equipment (GSE). The test was focused on the evaluation of the impulse bit (*Ibit*), propellant mass consumption (m_{bit}), specific impulse (*Isp*) and overall efficiency (η_{th}) during the entire thruster