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Firing test and evaluation of coaxial pulsed plasma thruster

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Abstract. For many reasons, electrical propulsion systems are the most expected in space; they are suitable for researchers because they are effective, easy to design and applicable in space. One of the most important parameters that could assess the performance of the propulsion system is the problem of measuring the very low thrust of pulsed plasma thrusters (PPTs). Various test beds, including indirect designs of measuring systems such as pendulums and optical measuring systems, can measure the thrust with very high precision, but it is very complicated.

This paper presents the firing test of a new designed coaxial pulsed plasma thruster for proofing the concept and then the thrust is measured by a new simple test bed using a rod in accordance with a loading cell (0-100 gf.) which can measure thrust accurately after good calibration up to μgf . In a medium-sized vacuum chamber (VC) (10^{-5} bar, $D=1$ m and $L=1.4$ m), a coaxial PPT is designed and tested under environmental conditions in space. Four proofs of concept took place until the experiment was adjusted and six experiments were carried out to measure the thrust using the new test bed under various operating conditions. Evaluation of the system is presented too and the maximum thrust obtained is 0.68mN at the discharge voltage equals 7kV and the 12kV voltage of the spark plug initiator and the efficiency equals 10%. The steps of fabrication of the coaxial PPT and steps of measuring the thrust is presented in the paper beside the result charts of the thrust under different operating conditions.

KEYWORDS: Pulsed plasma thrusters, performance parameters, firing test, measuring instruments.

1. Introduction

Pulsed plasma thrusters (PPT) is one of the electric propulsion systems which, due to the advantages of PPTs, can be considered as a research basis for a long time. The electrical propulsion system is considered to be the first in the world since 1964 and is largely included in the research schedule due to its ease of design, safety and low production costs. These advantages enable researchers to use PPTs for research in space programs such as Falconsat, Dowgstar[1] in scientific satellites. PPTs are not simple but complicated systems, which is why early PPTs ' performance could not be improved by researchers since their first conceptual design. Due to its high specific momentum, Isp and Low Mass, the researchers have been attracted to PPTs. The coaxial PPT type (Fig. 3) at the beginning was developed in the form of magnetoplasmadynamic device and then it is considered as a part of the PPT family [2]. Although some isolated laboratory devices gave efficiencies of the system up to 50%[1]-[2], but the PPTs in general operate in the range of 2% to 12%[3,4].

In order to initiate the ionization process within the PPT, a spark plug with a high voltage discharge, PPTs, is used. The energy generated by the condenser is transformed into an electromagnetic field generating the thrust of the PPTs, where the magnetic field concentrates the charged ion particles in the beam in order to obtain a valuable thrust and the electric field responsible for accelerating the charged ion particles at very high speeds (up to 1500 m/s) via the Lorentz force ($J \times B$ force). The PPTs ' common



design consists of various parts; Teflon™ as the Fuel, a capacitor for stored energy, power supply to charge the capacitor with energy, a discharge chamber containing electrode Plates to accelerate the ionized particles (Plasma) and a sparkplug to initiate the ionization process and start the discharge as shown in figure 1.

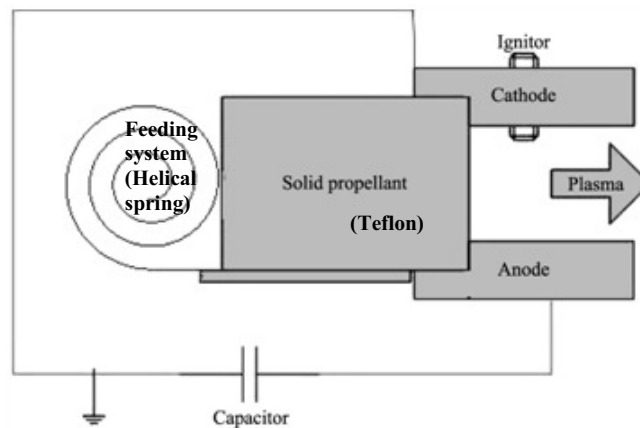


Figure 1. Scheme diagram of solid PPT.

In this research, the Otho Model is a coaxial PPT consists of a nozzle part made of Copper as the cathode, tungsten pen as the anode, a joint part made of aluminum, a rear isolating part made of Teflon, solid Teflon as the Fuel, mini spark-plug as an initiator and two Dc Power supplies (30 kV, 3 mA).

Due to difficulty to measure the thrust produced by PPTs (around mNs), different measurement mechanisms are used to determine the thrust with direct or indirect way of measurements such as (Thrust measurement Pendulum, optical laser measurement) which are very complicated mechanisms [4,5].

A simple new test bed is designed to allow the load cell (LC) sensor to measure the thrust Force with an amplification arm mechanism to amplify the produced thrust by the designed coaxial PPT (Otho Model).

2. Theoretical analysis

2.1. Design laws

Thrust, mass flow rate and power can be presented in the next equations,

$$F = f I_{bit} \quad (1)$$

$$\dot{m} = fm \quad (2)$$

$$P = fE \quad (3)$$

where f the frequency is I_{bit} is the impulse bit and E is the energy

Specific impulse and efficiency are presented by the next equations

$$I_{sp} = \frac{F}{\dot{m}g} = \frac{I_{bit}}{mg} \quad (4)$$

$$I_t = \frac{F}{P} = \frac{I_{bit}}{E} \quad (5)$$

The most commonly used units for I_{bit} is $\mu\text{N}\cdot\text{s}$, f is Hz, E is J and for m is kg .

2.2. Operation and analytic considerations

The thrust generated inside the PPT discharge chamber contains two portions of thrust, due to Lorentz force and gas expansion and the total thrust is presented as the sum of the two portions,

$$F = F_{L+} F_{Th} \quad (6)$$

where F_L is the portion of the thrust generated by the Lorentz force and T_{Th} the second portion which is generated by the gas expansion.

Even so, for the sake of general understanding of the physics of PPTs, the most common model for simple coaxial PPT can be described using the configuration geometry. So, from magnetic pressure the electromagnetic portion of impulse can be modeled as [6;7;8],

$$I_L = K \cdot \int_0^\tau i(t)^2 dt \quad (7)$$

$$K = \frac{\mu_0}{2\pi} \left[\ln \frac{r_{cathode}}{r_{anode}} + 0.75 \right] \quad (8)$$

where K is called the inductance gradient factor, $r_{Cathode}$ is the cathode inner diameter, r_{anode} is the anode diameter and μ_0 is the Vacuum permeability constant (1.257×10^{-6} H/m) and It is common to define the integration over the discharge period τ as:

$$\psi = \int_0^\tau i(t)^2 dt \quad (9)$$

where ψ is called the current parameter.

Approximate expression of the thermal gas expansion term is derived by Robert Vondra, From MIT, in the late 1970s[7]. The mass loss m_α and characteristic thermal Velocity c_α of each species is considered and then the gas expansion impulse can be modeled as,

$$I_{th} = \int_A dA \int_0^\tau nm(mv_i v_j) dt \approx \sum_\alpha m_\alpha c_\alpha \quad (10)$$

Thus, the theoretical total impulse bit could now be defined as,

$$I_{bit} = K \cdot \psi + \sum_\alpha m_\alpha c_\alpha \quad (11)$$

Considering average mass and thermal velocity for the species, m and \bar{c} , then the impulse bit can be simplified as follows,

$$I_{bit} = K \cdot \psi + m\bar{c} \quad (12)$$

From I_{bit} the thrust can be obtained using the basic design lows

$$\eta_t = \frac{F^2}{2\dot{m}P} = \frac{I_{bit}^2}{2mE} \quad (13)$$

where P is the Power, \dot{m} mass bit [9]

3. Hardware Development

Figure 2 shows the PPT power supply unit, the PPT during manufacturing and its final product.

The PPT consists of several hardware components which can be presented as:

- The Power Unit: Two power supplies, Fig.2.a, were tailor- made and produced in the laboratory where the electricity in the satellite is converted into high voltage and 4- 10 kV were used to maintain ionization in the discharge chamber. The activation of spark plug required about 15 kV.



a) Power unit (30kV, 3mA)

b) PT manufacturing

c) PT Final product

Figure 2. PPT power supply unit, manufacturing and final product.

do not take into account other forces. The power output of the LC is very small, and special amplification is required. The 1046 PhidgetBridge fortunately completes all the electrical output amplification and measurement.

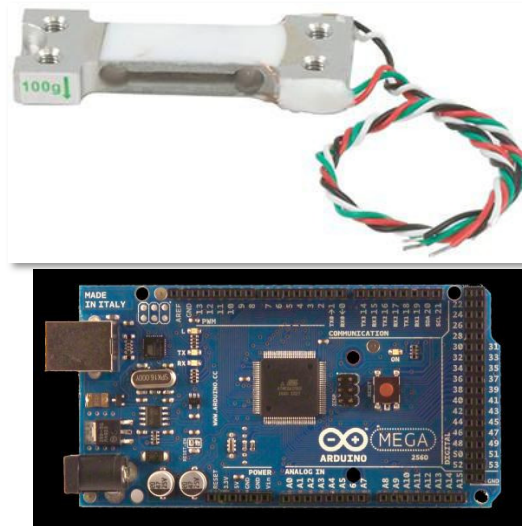


Figure 4. Thrust measuring tool, (0-100g) Micro LC and card Arduino Mega 2560

LC specifications:

- Weight: 100g
- Wheatstone Bridge Sensor
- Measuring shear force
- Dimensions: 35mm x 12mm x 4mm

The LC is connected to the laptop through a weight scale Analog-to-Digital converter (ADC) 24-bit amplifier, which converts the analog signal to Digital one through an Arduino data transfer Card Fig.4, all the measuring system is controlled by (Matlab program), figure5.

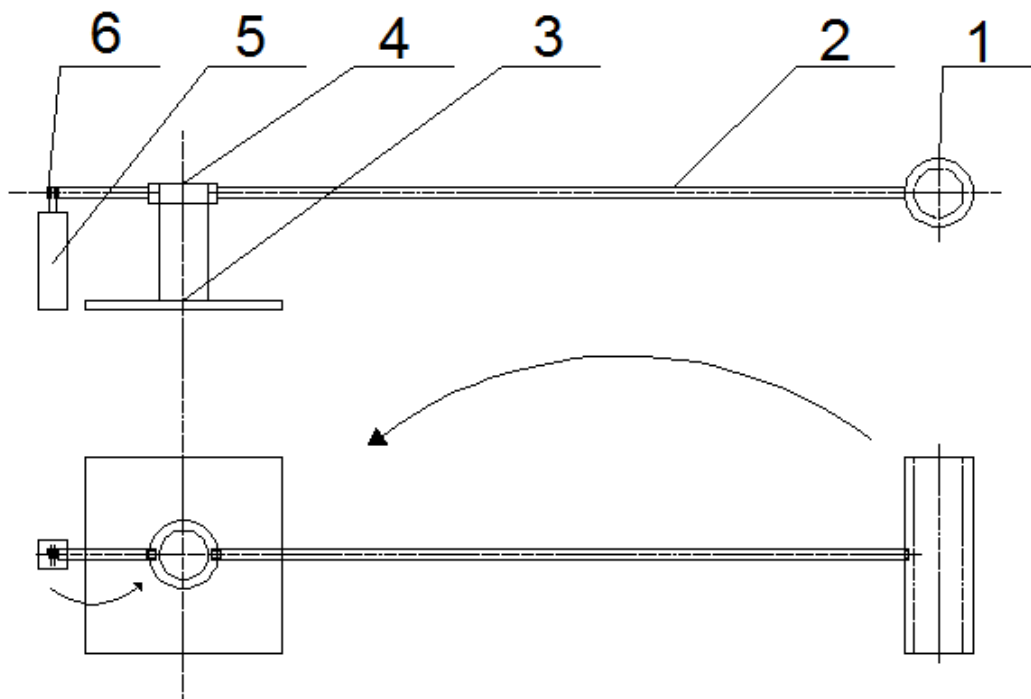


Figure 5. PPT measuring technique

5. Test bed and measuring mechanism

Using a very sensitive ball bearing, a new and simple mechanism is used for the measurement of the thrust force of PPT. The thrust can be measured by positioning the PPT thruster horizontally in one bar end and placing the pin on the other bar that touches the LC sensor and uses a preload force.

Figure 6 shows the scheme of fabricated thrust measuring mechanism using an arm for amplification and LC. While Fig. 7 presents some photos of the PPT which has been connected to the test bed thrust measuring mechanism.



(1-PPT, 2-Amplification arm, 3- base, 4- Roll bearing, 5-Sensor fixation, 6-LC Sensor)

Figure 6. Thrust measuring mechanism using amplification arm and LC

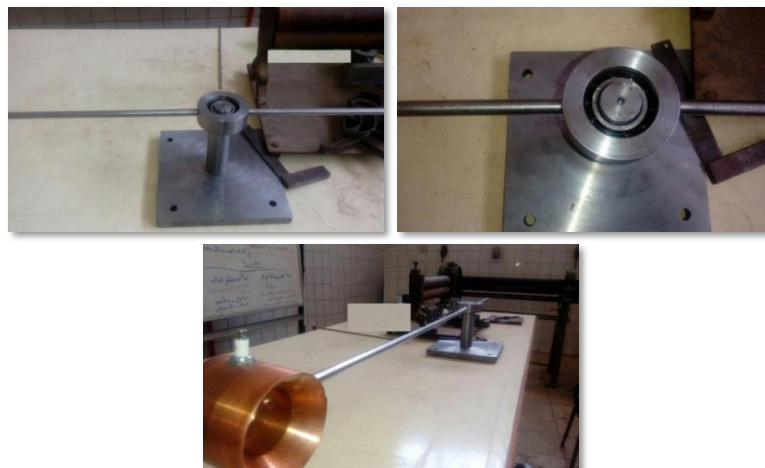


Figure 7. PPT test bed and measuring mechanism

Test setup for the coaxial PPT

The base plate of the test bed and the fabricated thrust measuring mechanism connected to the PPT is settled in VC and firing tests are accomplished.

A medium-size VC is used to achieve the desired vacuum conditions 1×10^{-5} Torr and different experiments have been carried out for concept tests and thrust measurement Fig8.

The test bed scheme describing the measurement process is shown in figure 8. This test bed uses the developed thrust measuring mechanism, figures 5,6 and 7, which is designed to amplify the very small

value of the PPT thrust by means of an amplification arm mechanism that can be measured and considered in future studies. A calibration process is carried out to set the LC accuracy and convert the voltage values into force readings.

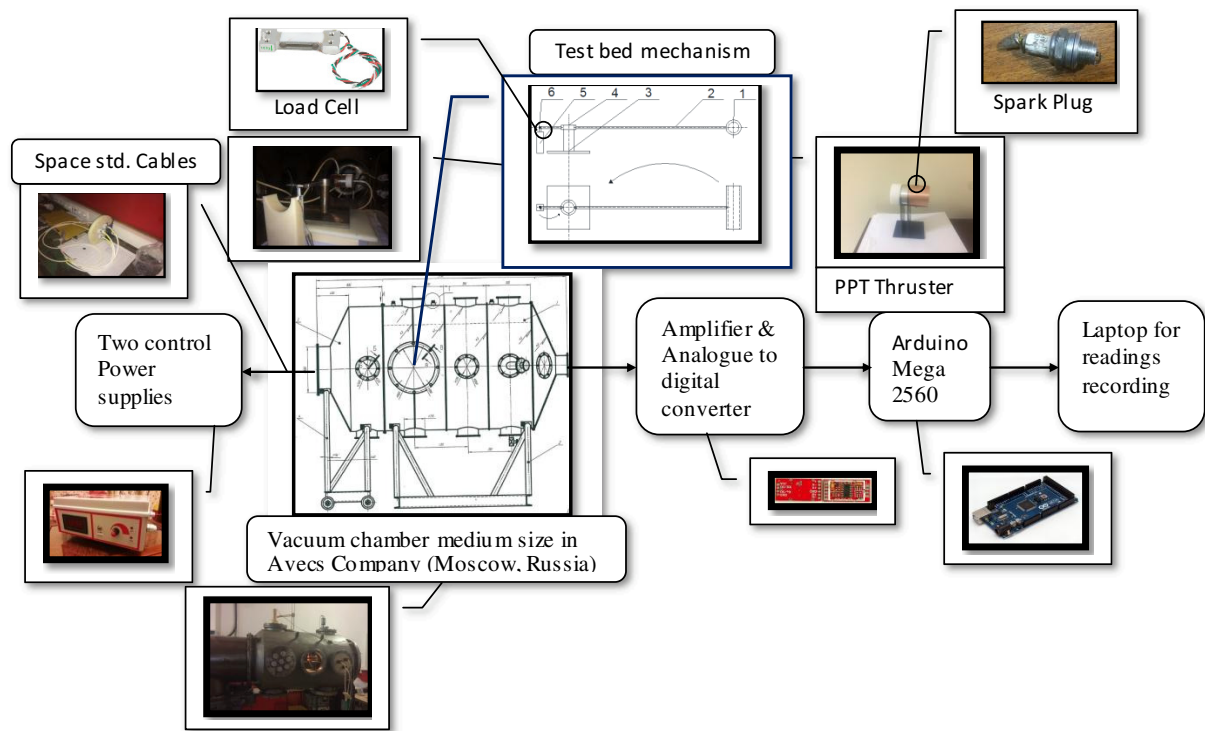


Figure 8. PPT test setup and measurement in VC

Figure 9 presents photos showing the PPT test setup, where figure 9.a shows the PPT test bed fixation inside the vacuum chamber. Figure 9.b presents PPT connecting cables. Figure 9.c presents the front part of the VC and figure 9.d presents thrust power supply connections to the PPT within the vacuum chamber.

6. Experimental procedure

- Fix the PPT test bed with the thrusting measuring mechanism in the vacuum chamber.
- Connect all cables including power supply and measuring data cables.
- Reach the required vacuum simulating the space environmental conditions (10⁻⁵ bar) usually the evacuation process of the medium VC takes place in time period (3-3.5) hours and preparation of the system in each attempt 1.5 hours and di-evacuation in 2 hours, so the summery of the total time period of each attempt is around 7 hours.
- Start the PPT firing test for proof of concept, figure 10.



a) PPT Test bed Fixation inside vacuum chamber

b) PPT connecting cables



c) PPT inside vacuum chamber

d) Vacuum chamber, with power supply connections

Figure 9. PPT test setup

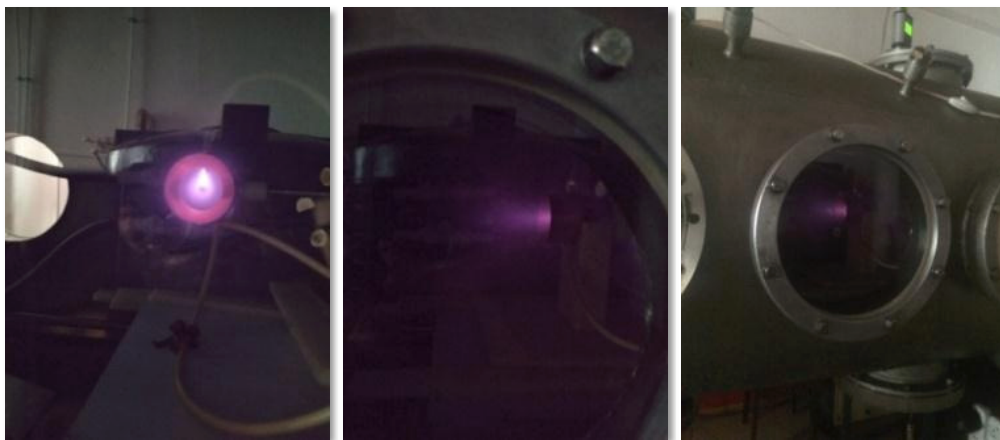
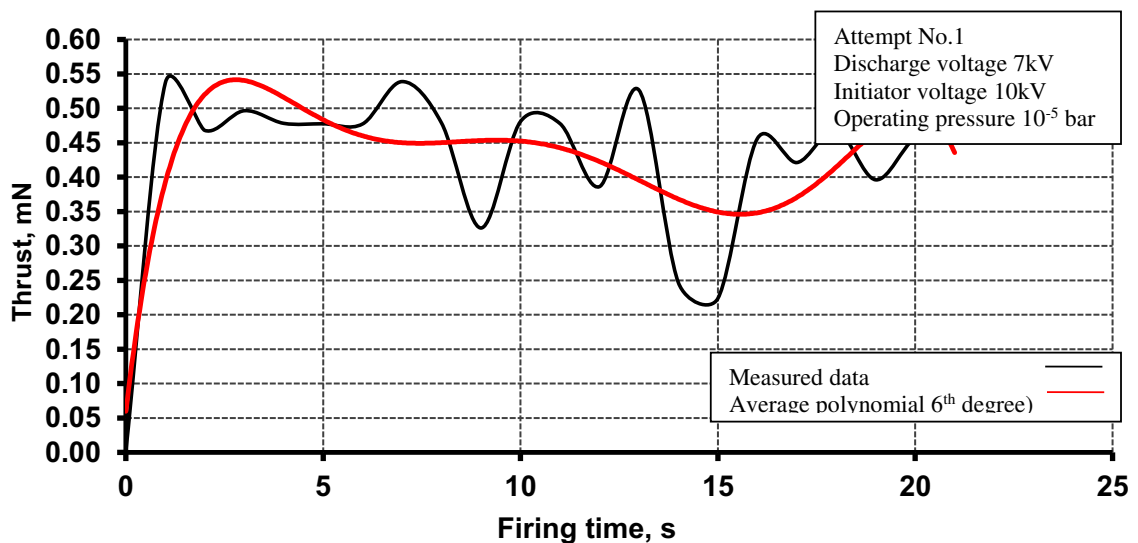


Figure 10. PPT firing test

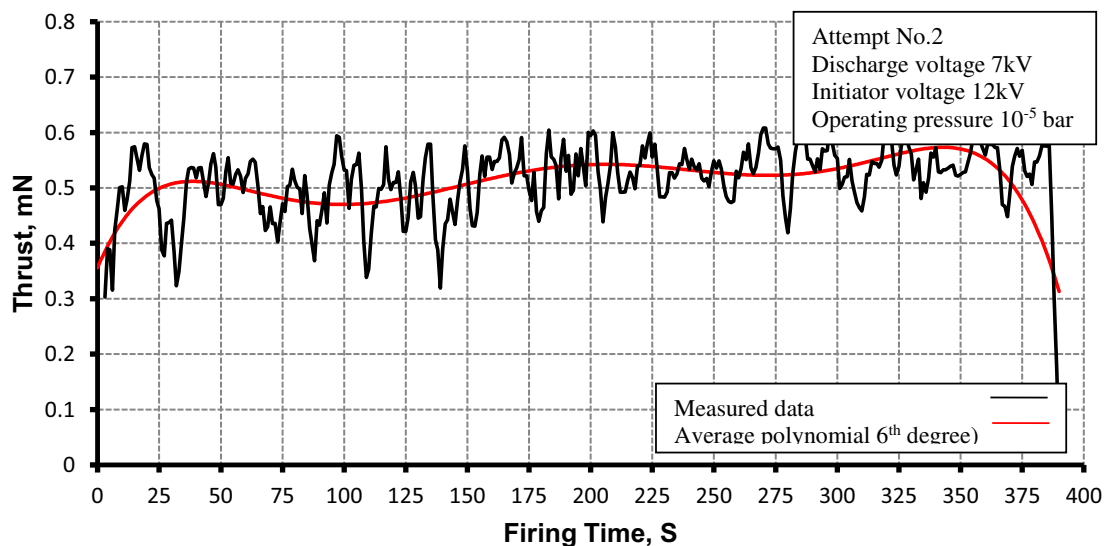
7. Thrust measuring results

When the operation of PPT Thruster is started, it pushes the end edge of the bar which in return pushes the pin placed at the edge of the other bar and increase the load applied to the LC. The measurements of the LC is recorded by the measuring system program and saved in WordPad file and these results will be drawn in charts against time by using excel program.

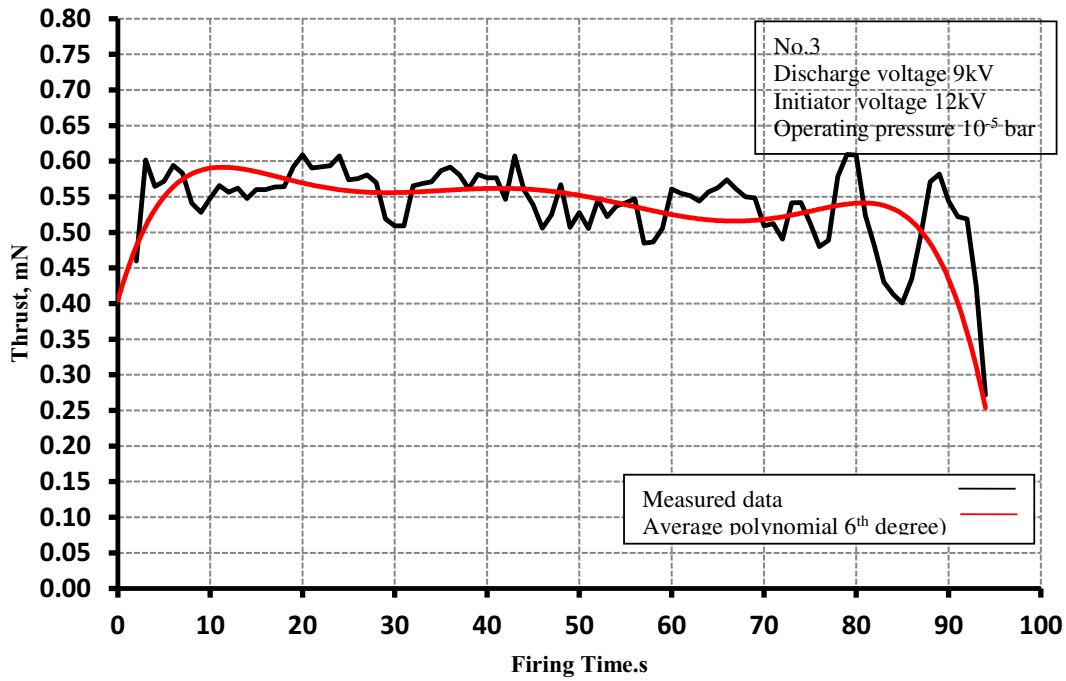
Six Experiments have been carried out for thrust measurement using the designed test bed to measure the thrust under different discharge voltages and different spark plug voltages for initiating the ionization process. The next charts, Figures 11.a to 11.f, show the different PPT measured thrust values under different discharge conditions.



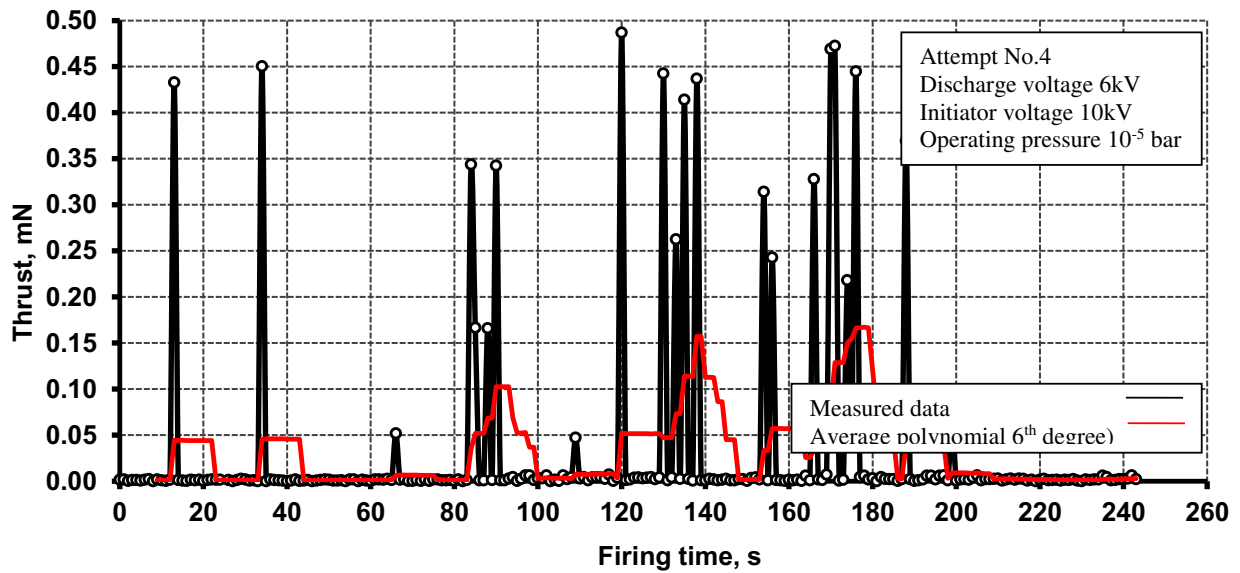
(a) 1st attempt for variation of thrust with firing time at discharge voltage 7kV and spark voltage 10kV



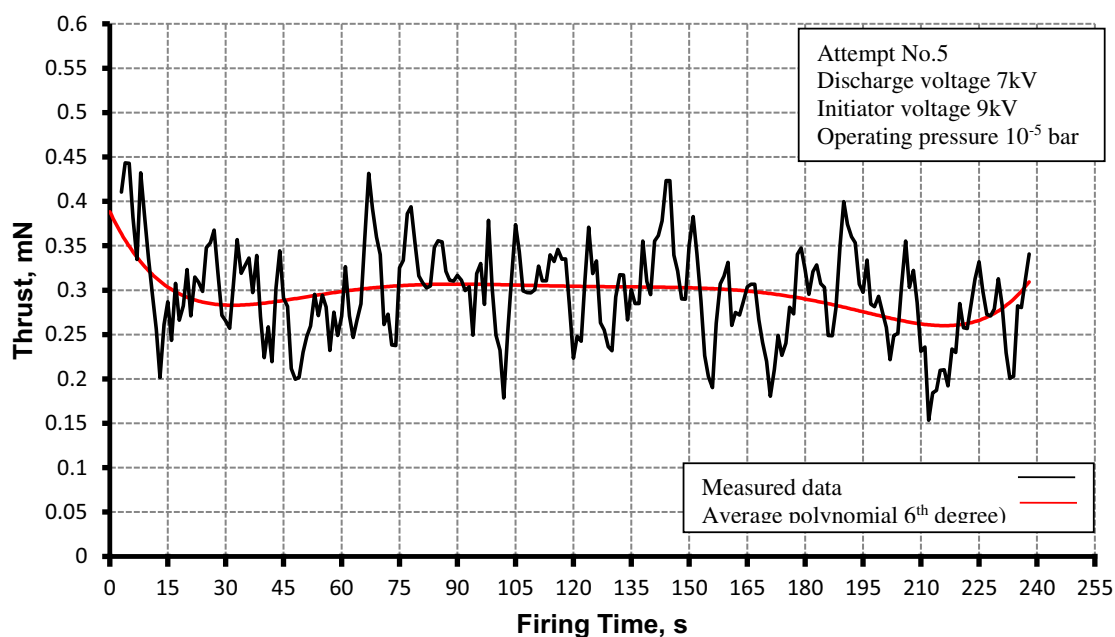
(b) 2nd attempt for variation of thrust with firing time at discharge voltage 7kV and spark voltage 12kV



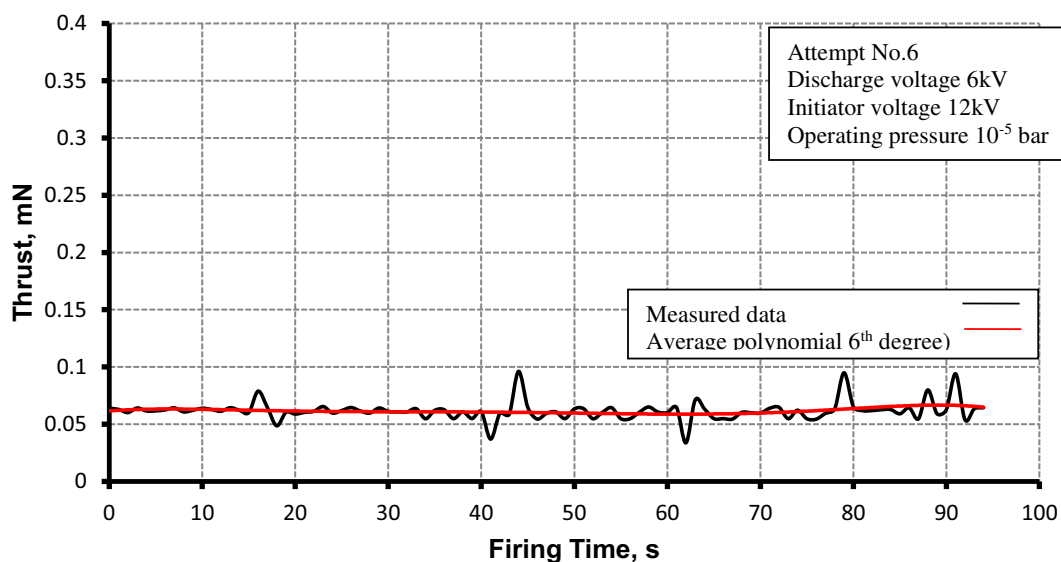
(c) 3rd attempt for variation of thrust with firing time at discharge voltage 9kV and spark voltage 12kV



(d) 4th attempt for variation of thrust with firing time at discharge voltage 6kV and spark voltage 10kV



(e) 5th attempt for variation of thrust with firing time at discharge voltage 7kV and spark voltage 9kV



(f) 6th attempt for variation of thrust with firing time at discharge voltage 6kV and spark voltage 12kV

Figure 11. PPT measured thrust as function of time under different discharge conditions

The results of firing tests can be evaluated as follows:

First attempt uses 7 kV for discharging against 10 kV for the spark plug and the experiment give good results and good plasma quality. This experiment takes place for 25 second as First measuring test.

Second attempt, 7kV for discharging against 12 kV is used for the spark plug initiator, again good plasma quality and good readings are obtained, this experiment took place for around 325 seconds. The thrust varied around a mean value due to non-sensitive measuring system according to indirect contact between the LC and the pin of the measuring arm. When direct contact obtained a very high noise appeared and a decision is made to just have slight contact between the LC and pin connected to the measuring arm.

Third attempt uses 9 kV for discharging against 12kV for the spark plug initiator, good plasma appeared and good readings for the thrust is obtained. Again, the thrust variation is noticeable due to the problem mentioned above; this experiment took place for around 90 seconds.

Fourth attempt, 6 kV for discharging against 10 kV are used for the spark plug initiator, weak plasma is appeared but thrust bad readings is obtained with some high thrust readings every 30 seconds or more, this experiment took place for around 240 seconds.

Fifth attempt uses 7 kV for discharging against 9 kV for the spark plug initiator, good plasma is appeared and good thrust readings is obtained with variations in readings due to the aforementioned reasons above, this experiment took place for around 240 seconds.

Last attempt, 6 kV for discharging against 10 kV are used for the spark plug initiator, weak plasma is appeared but very low thrust readings is obtained with variations in the readings due to the aforementioned reasons above, this experiment took place for around 90 seconds.

The standard configuration used for the PPT firing test is given in Table 1.

Table 1. Standard configuration for the PPT firing test.

PPT Parameters	Attempt number					
	First	Second	Third	Fourth	Fifth	Sixth
<u>High Voltage Discharge</u>						
Voltage, Kv	7	7	9	6	7	6
Current, mA	3	3	3	3	3	3
<u>Discharge Initiator</u>						
<u>(Spark Plug)</u>						
Type of Sparkplug	NGK	NGK	NGK	NGK	NGK	NGK
Voltage, Kv	10	12	12	10	9	12
Current, mA	3	3	3	3	3	3
<u>Electrodes</u>						
Cathode material	Copper	Copper	Copper	Copper	Copper	Copper
Diameter, mm	44	44	44	44	44	44
Anode material	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten
Diameter, mm	3	3	3	3	3	3
Length, mm	100	100	100	100	100	100
<u>Propellant</u>						
Material	Teflon	Teflon	Teflon	Teflon	Teflon	Teflon
Exposed diameter, mm	44	44	44	44	44	44
Thickness, mm	3	3	3	3	3	3
<u>Thrust</u>						
mean value, mN	0.4	0.62	0.60	0	0.35	0.35
<u>Specific impulse</u>						
Mean value	350	470	350	0	240	50
Experiment period, second	25	325	90	240	240	240
<u>Specific bit impulse</u>						
I_{bit}/E [$\mu\text{N}\cdot\text{s}/\text{J}$]	28	38	35	0	25	15
<u>Efficiency</u>						
η [%]	5	10	3	0	8	0.1

Most of the PPT Motors need more than 20 experiments to express the behavior and the performance of the system empirically because most of the designing parameters depends of previous experiments took place by different researchers and the only way to verify your model is to get empirical formulas expressing the performance of the system under different boundaries obliged by previous researchers.

Due to lake of time period available for the test experiments there was no chance to make more experiments needed to specify the performance of the motor by changing different effective parameters , a matrix between discharge voltage and spark plug initiator voltage was designed to analyze the behaviors of the motor and get optimum working conditions.

8. Mass flow rate

For noticing the erosion and mass consumption of TeflonTM, a sensitive mass balance was necessary to compare the mass before and after a number of discharges and to detect average mass loss per second.

The mass scale which is used was a Sartorius MC5 that was limited to a total sample mass of 10.1g and it is accuracy up to 1 μ g. This required that the Teflon used in the experiments was a thin slice with width of 2mm placed and clamped into position on the surface of a TeflonTM block. The measured mass flow rate (or mass bit) around 0.128 μ g.

9. Conclusions

A PPT design has been tested in a medium VCusing a new designed test bed under space environmental conditions and proof of concept experiments carried out for verifying the designed PPT and detecting best conditions. Six experiments carried out for measuring the thrust by the new designed test bed under several conditions.

- A Test bed mechanism is designed and has been used for measuring the thrust up to μ g force or mN by a (0-100g) LC sensor.
- Maximum thrust obtained is 0.68mN at discharge voltage equals 7kV and spark plug initiator voltage is 12kV which is considered as the best conditions, efficiency 10% and specific bit impulse 38 μ N-s/J.
- In Attempts 4 and 6 there are unknown reasons for ripples in curves which could be because of unstable plasma or un fixed contact point between the test bed mechanism and the LC used in the measuring test bed.
- A modified thrust measuring end for the mechanism is required to avoid such ripples and to get accurate continuous readings.

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