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Proof of Concept and Analytic Considerations of Coaxial Solid Pulsed Plasma Thrusters

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ABSTRACT: The objective of this article is concerning on the design, test setup and analytic study of pulsed plasma thruster (PPT). PPT can be used with small satellites (up to 500kg) at low earth orbit for various missions as launch correction, orbit transfer and orbit correction. PPT is considered one of the remarkable thrusters that can be used in space due to its easy design, low cost, high safety and long life time. PPT usually classified by the propellant type (Solid or liquid), electrode geometry (length, width and diameter) and materials (Aluminum, Brass, Tungsten etc...). A new design of solid coaxial PPT with TeflonTM as a solid propellant, brass as cathode electrode and tungsten as anode electrode is fabricated to achieve the proof of concept and firing tests under optimum working conditions as space environment. Four trials tests as proof of concept experiments take place to get working conditions for coaxial PPT design which could be used for nominal design and verified by five experimental tests to get optimum operating conditions in medium vacuum chamber (10^{-5} bar)(D=1 m, L=1.5 m). Analytic various specific impulse ($I_{sp,s}$) and efficiency are calculated according to real conditions considered to the real experiments took place in the vacuum chamber including real different time periods. At optimum conditions where discharge voltage is 7kV and initiator voltage is 12kV, specific impulse and efficiency are calculated where specific impulse is 400-450 s and efficiency is 11-13%.

KEYWORDS: Pulsed plasma thrusters, Vacuum chamber, performance parameters, electric propulsion system.

I. INTRODUCTION

PPT is being considered as a low cost, low mass and power, simple and highly efficient propulsion option for micro satellites. This relies on the fact that a PPT is a small and self-contained propulsion system that utilizes a solid TeflonTM propellant. TeflonTM has the advantage of being inert and non-toxic, higher molecular weight, giving the PPT system an additional benefit of being one of the safest propulsion systems.[1][2][3] The PPT is operated depending on range or (Voltage, Power) and charges a capacitor to (5-12kV). TeflonTM is then fed axially which its front has fixed distance related to the pair of electrodes charged by the capacitor. A spark plug igniter, which consists of a semiconductor surrounded by another set of electrodes, is then fired to create a small amount of plasma annularly between the electrodes. This allows the capacitor to discharge and ablate a small amount of the TeflonTM. This mass bit is then accelerated due to a combination of electromagnetic and gas dynamic forces producing thrust. A brief comprehensive description of the PPT, a kind of electromagnetic thruster, is due to Rayburn and Campbell [4][5].

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II. RELATED WORK

On 1970 GUMAN designed a pulsed plasma microthruster system which was built, flight and qualified, then it was delivered to the Massachusetts Institute of Technology (MIT) Lincoln Laboratory for installation in the LES-6 satellite. The system was designed to satisfy the requirements for east-west for the mission of stationkeeping of the spin stabilized, synchronous orbit satellite.[6]

The efficiency of PPT is almost very low, that limits its use in some conditions. The PPT for the LES8/9 has a efficiency of 7% and for the EO-1 is about 8%. The efficiency of PPT reported in recent years is rarely exceeds 15%. Many reasons for low efficiency such as the following. Firstly, PPT is inefficient when transferring stored capacitor energy into acceleration of the ionized propellant. Secondly, mass utilization efficiency in PPT is low (< 50%) because of two performance robbing processes late-time vaporization [5] and macro-particles ejection. Big amount particles of the propellant are wasted as propellant vapour and large chunks. The thrusters usually have very low efficiency according to the combination of poor energy coupling into the propellant, late-time ablation, and inefficient acceleration. To improve the lower thrust efficiency more studies are needed about particles acceleration.[7][8]

III. EXPERIMENTAL WORK

The laboratory PPT system comprises of several hardware components which can be generalized as:

- The Power Unit – Fig.1 It is used to convert the energy in laboratory into high voltage, two power supplies (30kV, 3mA) Fig.(1.a) are tailored made in the laboratory, where 4-5 kV needed to keep the discharge in the discharge chamber and 15kV needed for the spark Plug activation.
- Discharge Chamber with nozzle (1) Fig.2.a&b where the fuel surface is ionized charged and accelerated by the electric field. The chamber geometry may also affect the acceleration properties of the plasma (Distance between electrodes, distance between spark plug and fuel surface ... etc). The electrode separation distance is non-adjustable and set to 20.5 mm (set up to 30mm) [9.10.11]. The discharge chamber works as the Cathode is made of red copper and ended by a coaxial red copper nozzle Fig. 2.a (44 mm inner Diameter and 70 mm outer Diameter), Fig. 2.c. A Tungsten pen (Diameter 3 mm with 100 mm length) works as the Anode, Fig. 2.d with sharp edge (flat edges have lower efficiencies than sharp edges).
- A rear part (3) is made from Teflon™ to keep the isolation between the two electrodes.



Fig. (1) The power unit

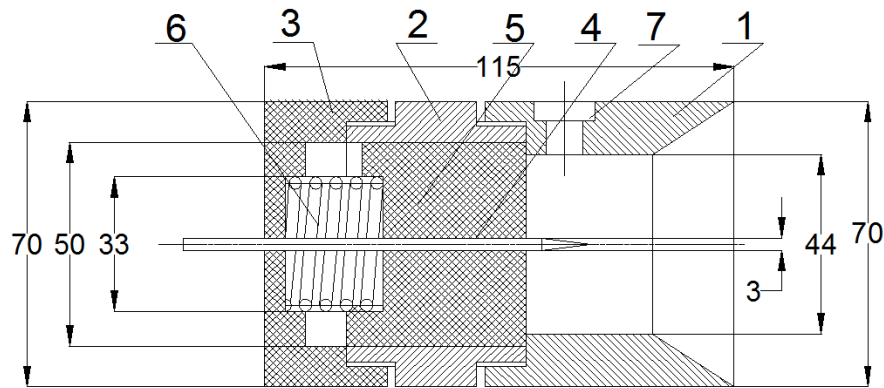
Fig.(1): Photos of the two power supplies (30kV, 3mA), PPT production and assembly.

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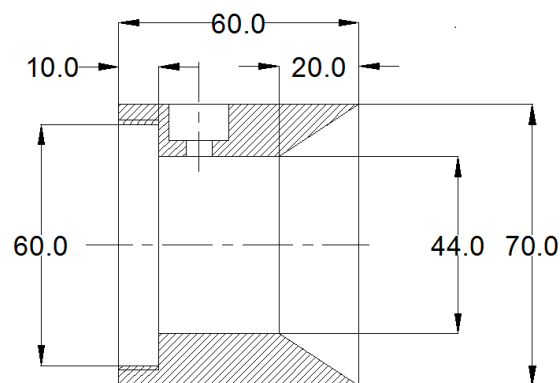


- 1- Discharge chamber (Cathode) with Nozzle
- 2-AL separation pat
- 3-Teflon rear part as insulator
- 4- Tungsten Pen (Anode)
- 5- Teflon fuel
- 6- spring
- 7- Spark plug mounting position

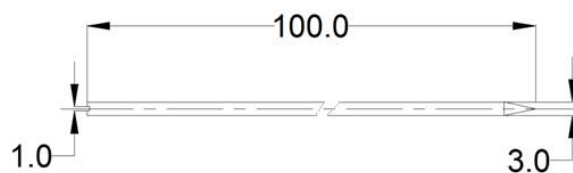
(a) Schematic drawing of PPT



(b) Photo of the PPT and during manufacturing



(c) Discharge chamber with nozzle (Cathode)



(d) Tungsten pen (Anode)

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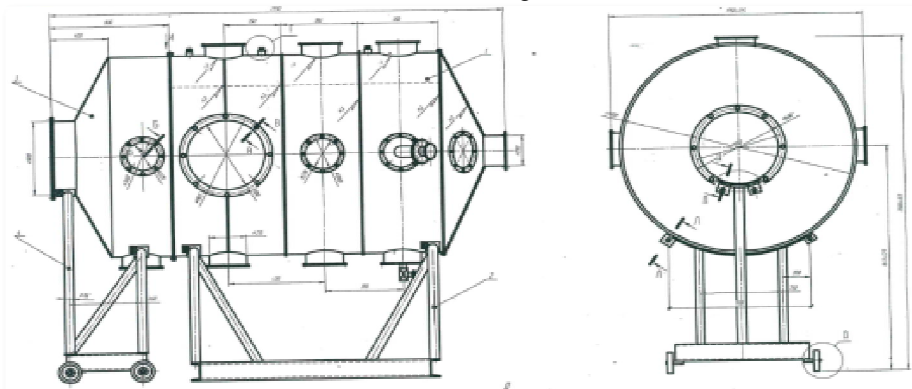
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(e): NGK 5812 CM-6 Standard Plug

Fig. (2) PPT parts schematic drawing

- The two electrodes (Anode and Cathode) (Fig.2.b)
 - Discharge chamber with nozzle (Cathode) a red Copper is used as a cathode due to its high electric connectivity and solidity.
 - Anode Tungsten pen (10 cm) with sharp edge (flat edges have lower efficiencies than sharp edges).
- Discharge Initiator (Fig.2.e) A spark Plug NGK is applied to initiate the ionization process of the fuel particles to create the required thrust.
- Fuel (5), Fig.2.a The fuel provides the mass to the plasma which is accelerated in the discharge chamber (usually Teflon™ according to its easy ionization, heavy particles and has little digassation in vacuum chamber and in space).
- Feed System (6), Fig.2.a A spring is applied to keep fixed distance between the fuel and the spark initiator.
- Vacuum chamber - A medium size vacuum chamber Fig(3) is used From



(a) Elevation and side view of the vacuum chamber



(b) Photos of the vacuum chamber

Fig. (3): A medium size vacuum chamber

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IV. PROOF OF CONCEPT

A connection disc Fig (4) is made of polymers to interface between the PPT placed inside the vacuum chamber and the control power system placed outside the vacuum chamber.

Space standard cables are used to connect the two power supplies and the PPT inside the vacuum chamber for the second trial after unsuccessful first trial. These cables are separated from each other with Epoxy Resin to prevent any short circuit due to very high voltage used for discharging process between electrodes inside vacuum chamber.

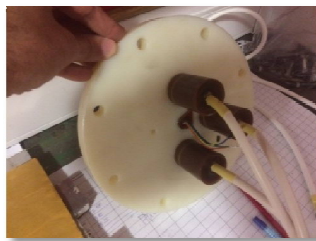


Fig. (4): Connection disc with Space standard cables for vacuum chamber

First trial takes place after suitable preparations and setup of the PPT inside the vacuum chamber Fig (5). A proof of concept experiment takes place under pressure 6.5×10^{-5} Torr and weak plasma appeared inside the Copper nozzle for 300 seconds then a very high vibration appeared between the power supply cables due to magnetic field between cables of power supply and the experiment is stopped due to safety precautions.

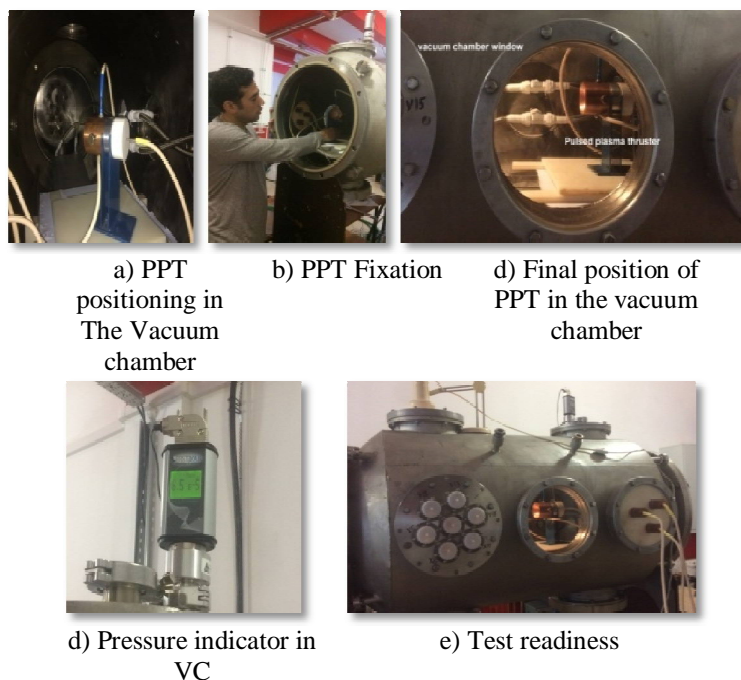


Fig. (5): PPT setup inside vacuum chamber.

A decision is taken to replace all cables for power supplies with space standard ones, also the poles are changed with each other (Copper anode and Tungsten cathode) and setting up the test again to verify the proof of concept experiment.

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Second trial for proof of concept is started but no plasma is appeared and a quick decision is taken to change again the poles as first experiment, where weak plasma appears inside the nozzle for 15 s approximately then the experiment is stopped to check the reasons.

After visual inspection of the whole system, it is found out that the spacing distance between the two poles of the spark plug is zero which couldn't initiate the plasma.

More modifications were made by fixing the spacing distance between the spark plug poles, sharpening the anode edges, cleaning the Teflon bar surface and after that again setting up the system inside the vacuum chamber for another proof of concept experiment.

Third trial for proof of concept takes place and a very strong plasma appears Fig (6) and spread from all open holes of the PPT, from the PPT nozzle, the hole where the spark plug is placed and strong plasma appeared in the rear part of the PPT beside all of that a continues spark appears in the ceramic upper part of the spark plug.

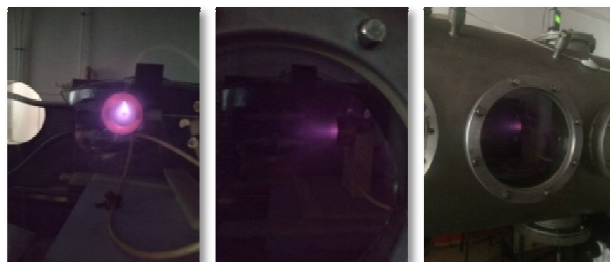


Fig. (6) PPT firing test in vacuum chamber

After inspection, it is found that plasma appeared in the rear part of the PPT due to high voltage between the anode and the metallic holder which worked as a cathode also and it is the reason for ionizing the rear part of the PPT which is made of Teflon. While the plasma spreading from the spark plug mounting position is due to small spacing between the spark plug and the fixing hole, the plasma spreads from this spacing. To solve these problems, the metallic holder of the PPT is replaced with acrylic holder, isolating cables inside chamber took place to avoid short circuits by using white epoxy and checking all connectivity between cables from outside and inside the vacuum chamber by voltmeter and the spacing between the spark plug and the fixing hole is filled with foam. The reason for the spark appeared in the ceramic upper part of the spark plug is not solved and using a new Spark plug is the only way to continue the experiments.



Fig. (7): Visual inspection of the Spark plug.

Forth trial for proof of concept experiment takes place to check the applied precautions for getting normal plasma. After preparation and safety instructions, very good continuous plasma appeared from the PPT nozzle for 300 seconds, Fig.8.

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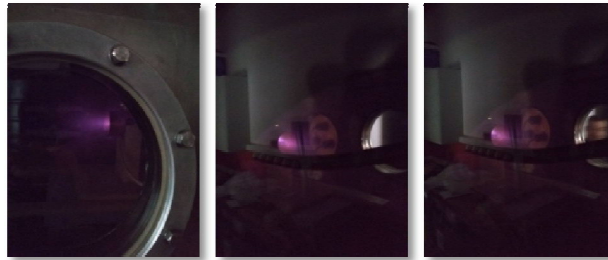


Fig. (8): PPT final firing test.

Photos of the plasma plume inside the vacuum chamber under pressure 10^{-5} bar, side view and frontal view are shown and the strength of the plasma obtained is clear.

V. ANALYTICAL EVALUATION

The basic operation of the PPT is usually divided in three main parts, the energy storage, ignition and main discharge. The resultant plasma is highly complex and has several species in its composition resulting from the breaking of the propellant long molecule. Due to the action of the Lorentz force and thermal gas expansion thrust is generated for a given PPT, the resultant thrust T as the sum [9].

$$T = T_L + T_{Th} \quad (1)$$

Where T_L is the thrust generated by the Lorentz force and T_{Th} by the gas expansion force. Each term of the thrust must be modeled according to the geometry and configuration of a designed thrust.

From magnetic pressure the electromagnetic portion of impulse I_L can be expressed as [12]

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

$$K = \frac{\mu_0}{2\pi} \left[\ln \frac{r_{cathode}}{r_{anode}} + 0.75 \right] \quad (3)$$

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 (1.257×10^{-6} H/m) and It is common to define the integration over the discharge period τ as:

$$\Psi = \int_0^\tau i(t)^2 dt \quad (4)$$

Where Ψ is the current parameter.

Robert Vondra, From MIT, Derived in the late 1970s, an approximately expression for the thermal gas expansion term [12]. Considering the mass loss m_α and characteristic thermal Velocity c_α of each species, the gas expansion impulse can be modeled as,

$$I_{th} = \int_A dA \int_0^\tau nm(mv_i v_j) dt \approx \sum_\alpha m_\alpha c_\alpha \quad (5)$$

Thus, it is possible to define the theoretical total impulse bit as,

$$I_{bit} = K \cdot \Psi + \sum_\alpha m_\alpha c_\alpha \quad (6)$$

If it is considered an average mass and thermal velocity for the species, m and \bar{c} , then the impulse bit is simplified and becomes,

$$I_{bit} = K \cdot \Psi + m\bar{c} \quad (7)$$

The simplified theoretical model for specific impulse I_{sp} and the thrust efficiency η_t becomes,

$$I_{sp} = \frac{T}{mg} = \frac{I_{bit}}{mg} = \frac{I_L}{mg} + \frac{\bar{c}}{g} \quad (8)$$

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$$\eta_t = \frac{T^2}{2mP} = \frac{I_{bit}^2}{2mE} = g \frac{I_{sp} I_{bit}}{2E} = \frac{I_L}{2mE} + \frac{c_{IL}}{E} + \frac{m\bar{c}}{2E} \quad (9)$$

Where P is the power and E is the energy

VI. RESULTS AND ANALYSIS

Using Matlab program to calculate the specific impulse and the analytic efficiency of the system by using the measured thrust varied with time during firing test. The calculated specific impulse and analytic efficiency for the five firing tests are shown in Fig.9 to Fig.18.

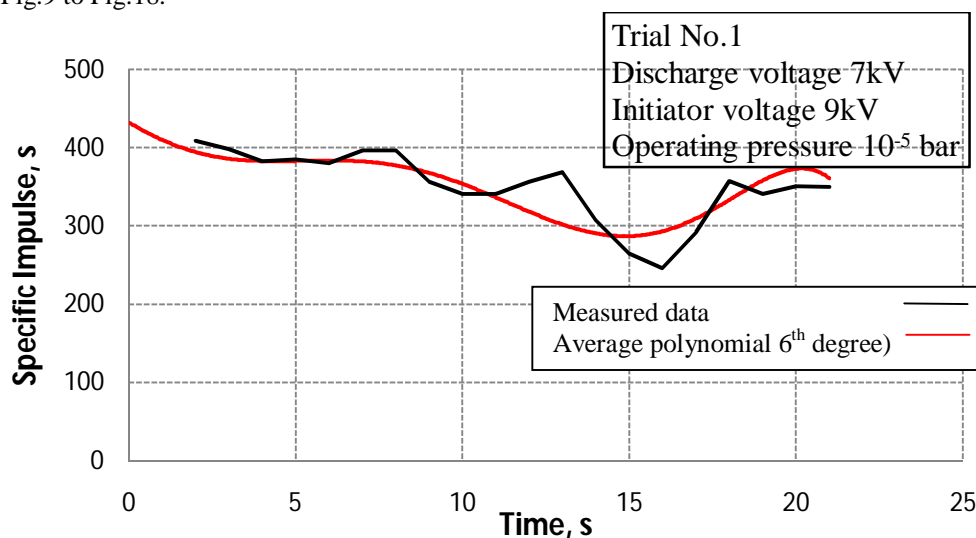


Fig (9) 1st attempt for analytic specific impulse

In this trial Specific impulse varies between 300-400s but mostly around 350s and it accepted.

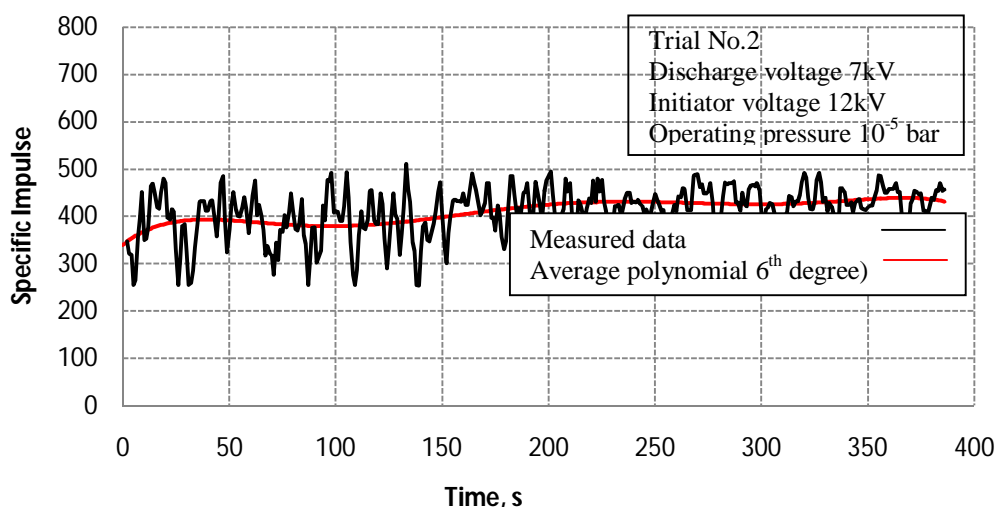


Fig (10) 2nd attempt for analytic specific impulse

In this trial Specific impulse varies between 300-480s but mostly around 420s and it accepted.

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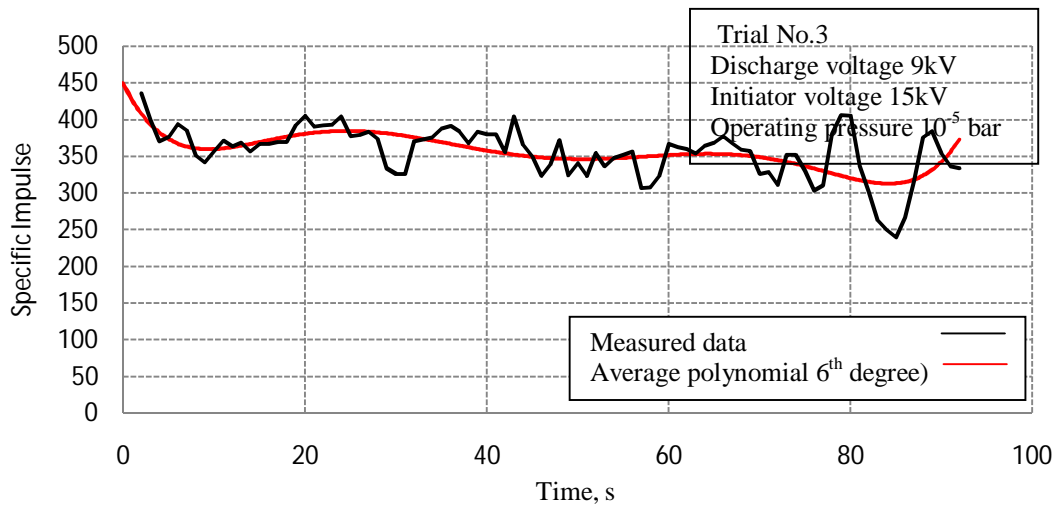


Fig (11) 3rd attempt for analytic specific impulse

In this trial Specific impulse varies between 300-400s but mostly around 350s and it accepted.

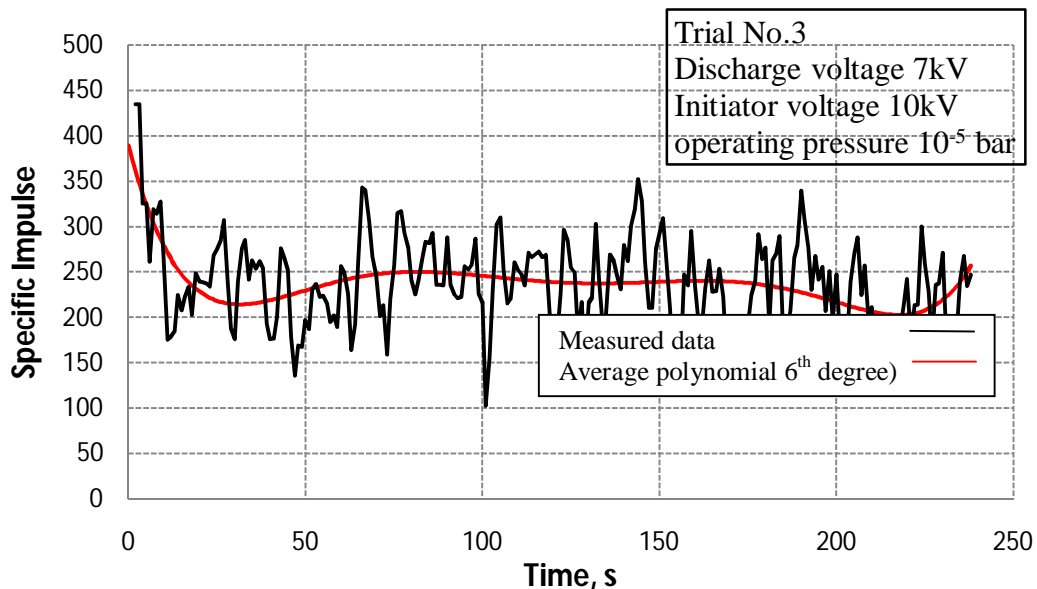


Fig (12) 4th attempt for analytic specific impulse

In this trial Specific impulse varies between 200-300s but mostly around 240s and it accepted.

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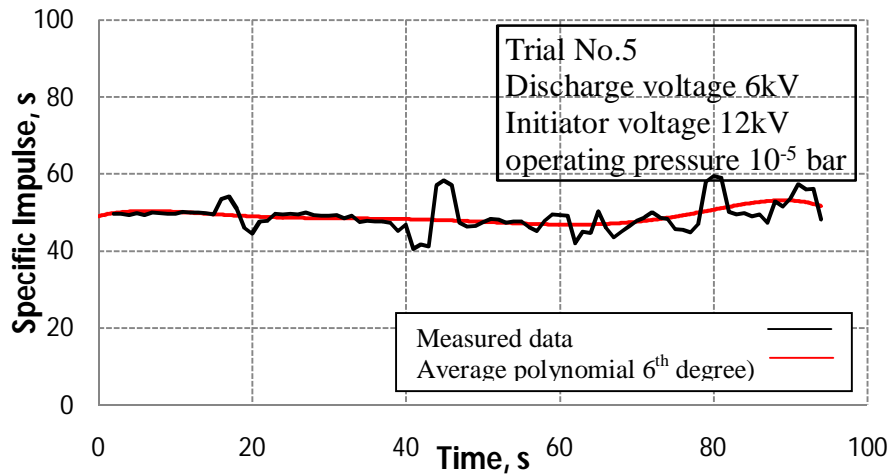


Fig (13) 5th attempt for analytic specific impulse

In this trial Specific impulse varies between 45-55s but mostly around 50s and it not accepted.

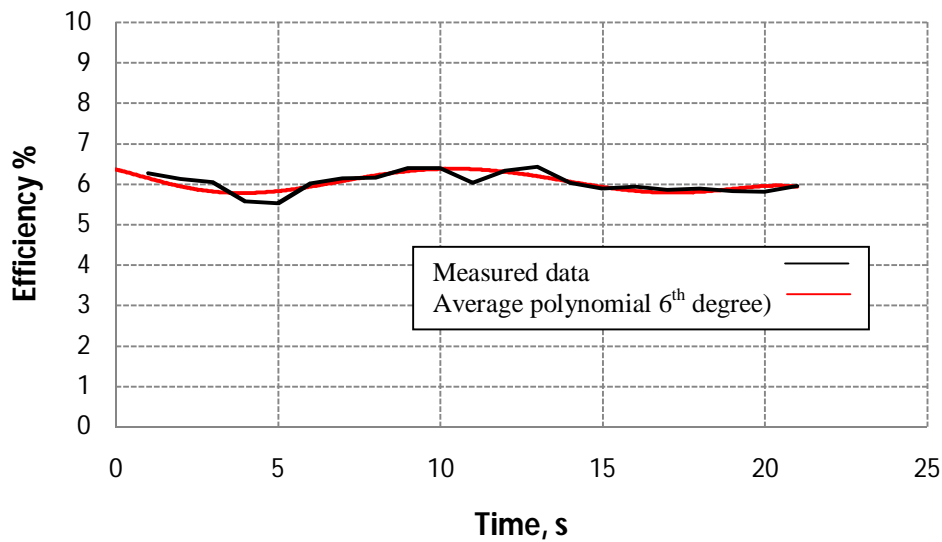


Fig (14) 1st attempt for analytic efficiency

In this trial efficiency varies between 1.8-2.1% but mostly around 2% and it is very low and not acceptable

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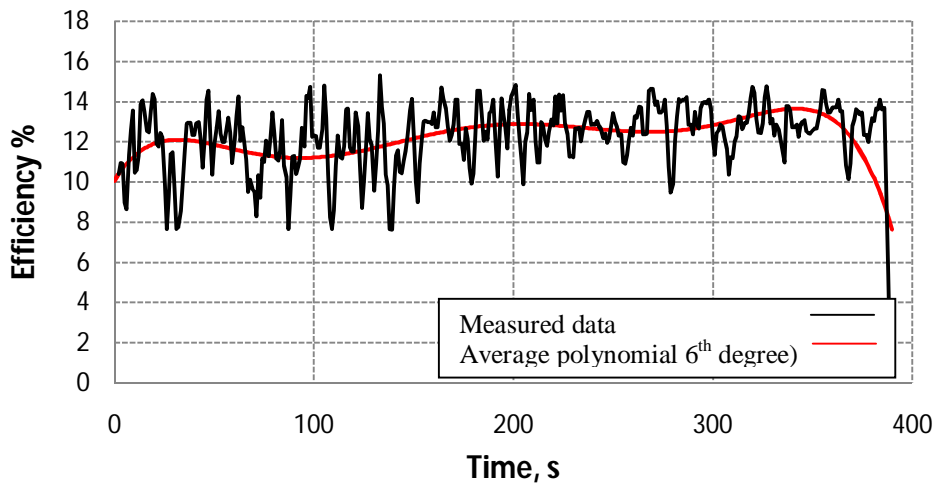


Fig (15) 2nd attempt for analytic efficiency

In this trial efficiency varies between 10-14% but mostly around 12.5% and it is acceptable

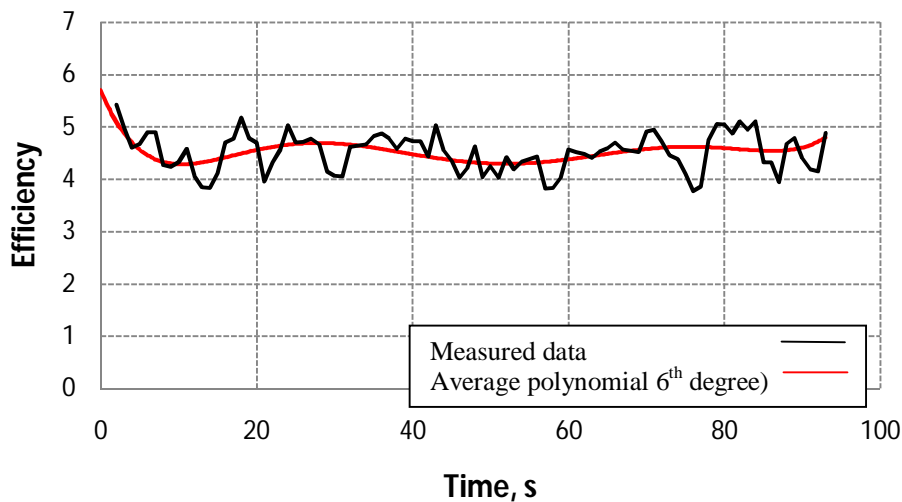


Fig (16) 3rd attempt for analytic efficiency

In this trial efficiency varies between 5-7% but mostly around 6% and it is very low and not acceptable.

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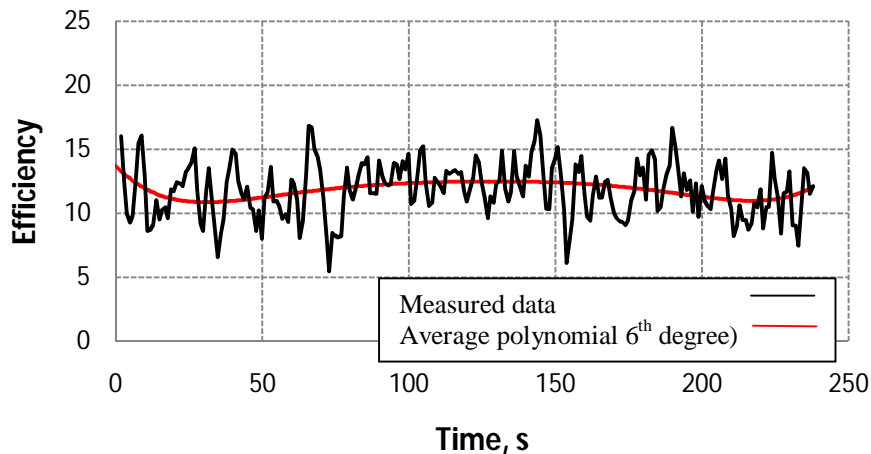


Fig (17) 4th attempt for analytic efficiency

In this trial efficiency varies between 10-14% but mostly around 12% and it is acceptable.

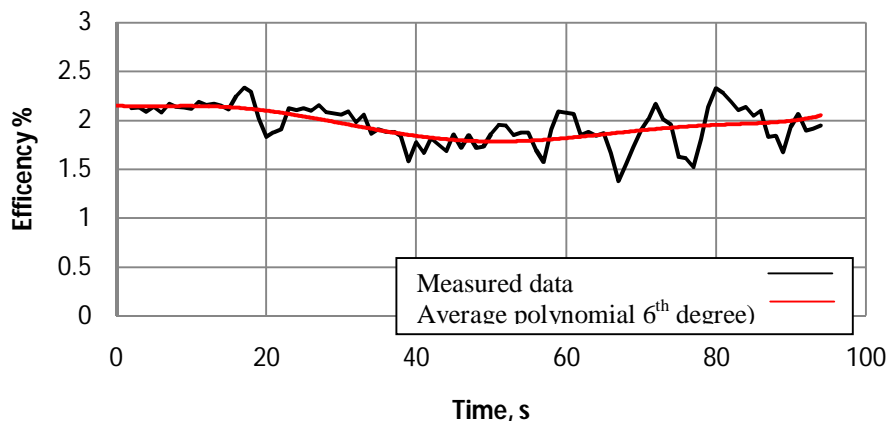


Fig (18) 5th attempt for analytic efficiency

In this trial efficiency varies between 1.5-2.5% but mostly around 2% and it is very low and not acceptable

VII. CONCLUSION

A new coaxial PPT is designed under the requirements and governing constrains to be able to produce an optimum thrust and to get the best working and operating conditions to achieve the tasks and tests needed from the design and to get its performance through the following conclusions:

- Four Proof of concept experiments took place till acceptable working conditions are detected, and 6 experiments with different voltage conditions and time periods take place under different conditions to get the best operating conditions.
- Five experiments are successful and one failed because of low discharge and initiation voltage (6kV) and (10kV) respectively.
- A successful PPT Thruster design is tested where proof of concept is reached in a medium size vacuum chamber.

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- Analytic specific impulse and efficiency are calculated according real measured conditions in the vacuum chamber including real different time periods.
- The best conditions correspond to discharge voltage 7kV and initiator voltage 12kV where specific impulse and efficiency are calculated. The calculated specific impulse reaches about 400-450 s and efficiency lies between 11-13% which is acceptable for PPT

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