Low Power Ablative Pulsed Plasma Thrusters

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Abstract: Ablative Pulsed Plasma Thrusters (APPTs) were the first Electric Propulsion (EP) devices to be flown onboard a real spacecraft and until nowadays continue to be among the most reliable thrusters to be used as main or secondary propulsion system, in small scale space missions. The down side is that their physics presents great complexity and it is not a trivial job to have precise physical models that can forecast the performance or characteristics of APPTs. Thus, much work has been done in order to characterize the general behavior of APPTs and to establish semi-empirical laws that could help the design process of such thrusters. Notwithstanding these efforts, the semi-empirical laws have not achieved perfect success in matching the forecasts with the experimental data, especially in the low-power regime of operation (below 10 J). Thereby, taking into account the recent efforts by the community to improve these semi-empirical models and to present general reviews of data, this paper aims to present a novel approach to the interpretation of experimental data of APPTs in the low-power regime. Special attention will be given to the coaxial configuration, which seems especially promising at low discharge energies. The aim is to develop a new set of formulas that will be useful for the design of high-efficiency configurations for low-power APPT propulsion systems, which are going to find increasingly wider application in the growing market of micro, nano and pico-satellites.

Nomenclature

A_p = exposed area of propellant
α = parameter of power law
β = proportionality parameter
c_α = thermal velocity of a given species
$\bar{c}$ = average thermal velocity of the gas
E = discharge energy

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η_t = thrust efficiency
f = pulse frequency of the thruster
g = gravity acceleration of Earth
h = height of rectangular electrode
i = discharge current
I_{bit} = impulse-bit
I_L = electromagnetic portion of impulse
I_{sp} = specific impulse
I_t = specific thrust
k_1 = semi-empirical power law parameter
k_2 = semi-empirical power law parameter
m = mass shot in each pulse
$\dot{m}$ = steady-state mass flow rate
m_α = mass of a given species
μ_0 = vacuum permeability
P = steady-state discharge power
Ψ = current parameter
R^2 = coefficient of determination
T = steady-state thrust
T_L = electromagnetic portion of thrust
T_{Th} = thermal expansion portion of thrust
τ = discharge period
w = width of rectangular electrode

I. Introduction

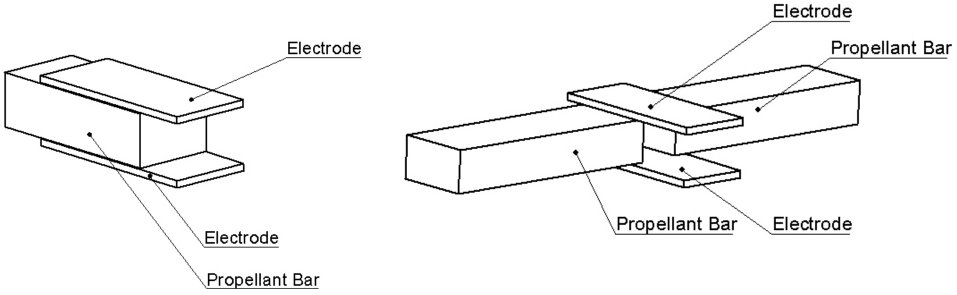
THE acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces", this is one of the most general definitions of Electric Propulsion (EP), given by Professor Robert G. Jahn, one of the precursors of EP activities in US, in the late 1960s[1]. This kind of technology, which is increasingly critical for the spacecraft community, has a peculiar approach to the space propulsion problem and, in contrast with the chemical systems, focuses mainly on the elevation of the specific impulse (up to thousands of seconds), sacrificing the thrust magnitude, ranging from a few μN up to $1N$. The main advantage in the utilization of EP is the high efficiency of the propellant mass utilization[1], in other words, it is possible to decrease the amount of propellant necessary to impart a given ΔV to a space vehicle. Additionally, the thrust energy of an EP thruster is not limited by the molecular bonds of the propellant, what happens in the chemical thrusters, and only depends on the power output of the electric source, thus having virtually no limit[2].

Currently, EP has many important applications, and mainly due to its very low propellant consumption, nowadays many companies, institutes and agencies of the space community choose to use these thrusters onboard their spacecrafts. The main applications are described by Turner[2]: *station keeping*, correcting of the orbit path and the compensation of the environmental perturbations; *transfer maneuver*, transferring of space vehicles between different orbits (usually from LEO to GEO); *interplanetary/lunar missions*, application of EP to interplanetary and lunar travels with high payload mass fractions.

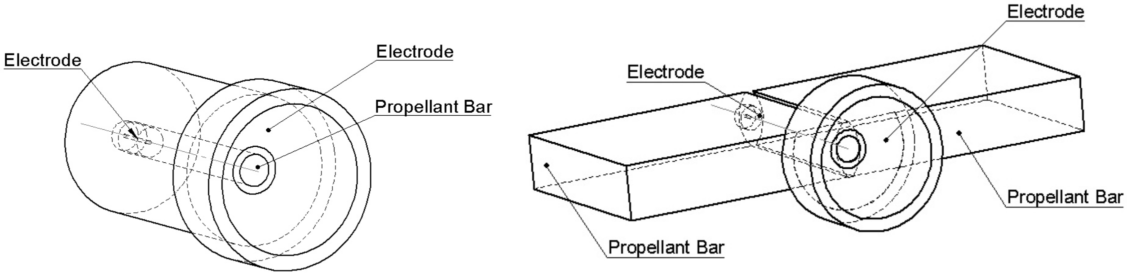
Between the many EP concepts conceived so far, the Ablative Pulsed Plasma Thruster (APPT) is one of the most simple, reliable and trusted propulsion systems ever made. Using a solid polymer as propellant (usually Teflon®), it uses high voltage pulsed discharges to ablate, ionize and accelerate the propellant, thus producing thrust. Because of its simplicity these were among the first types of electric thrusters to be developed and tested, both in the former Soviet Union and, later, in the United States. Therewith, in 1964, it became also the first EP system to actually be flown on a spacecraft, the Soviet probe Zond 2, on an unsuccessful (for reasons unrelated to the APPTs) mission to Mars, shortly before an ion thruster was sent into a suborbital flight aboard the SERT 1 spacecraft by the Unites States[3].

The basic operation idea of the APPT, described in details by[4], is based on an electronic circuitry that stores energy in a capacitor bank and cyclically discharges it producing pulsed high voltage arcs (some thousands of Volts) on the surface of the propellant bar, causing its vaporization, dissociation (known as the ablation process) and ionization. Part of the resulting gas is accelerated by the effect of the Lorentz force and other part by thermal expansion - resulting in the generation of thrust. Currently exists four most common types of APPT geometric configurations described in the literature [3], each of them greatly influencing both the performance of the thruster and its complexity of implementation aboard the spacecraft. These types are basically defined by the combination of two characteristics, electrode arrangement (usually rectangular or coaxial) and propellant feeding method (usually breech-fed, side-fed and "erosion" type). The four common combinations are:

- *Rectangular Breech-fed* (Figure 1a): It is the oldest configuration. The thruster is fed by just one rectangular propellant bar that is located between two parallel electrode plates. As the propellant is being consumed, a spring pushes the bar ahead, so that the propellant remains always between the electrodes.
- *Rectangular Side-fed* (Figure 1b): This configuration is similar to the first one, but the thruster is fed by two propellant bars located at opposite sides of the parallel rectangular electrodes.
- *Coaxial "erosion" fed* (Figure 1c): Originally designed to be a magnetoplasmadynamic (MPD) thruster. In this configuration, the propellant is a cylinder with an axial hole, so that the electrodes are located coaxially. Usually the cathode is located at the center of the cylinder and the anode externally. The fuel forms the wall of the discharge chamber and the propellant bar is consumed without continuously being refilled.
- *Coaxial Side-fed* (Figure 1d): It has similar discharge and electrode geometry from the last one but the propellant is composed by two bars at opposite sides.



(a) Rectangular Breech-fed APPT (b) Rectangular Side-fed APPT



(c) Coaxial "erosion" APPT (d) Coaxial Side-fed APPT

Figure 1. Main geometric configurations of APPTs.

Despite their relatively low efficiency, APPTs have been employed because of their outstanding reliability. The absence of tanks, piping and moving parts in general makes them very little prone to malfunctioning and failure, while at the same time easy to scale down to low power levels. This caused a resurgence of interest in APPTs in the 1990s[5,6] and has made them even more attractive in recent years, as increasingly smaller satellites, down to CubeSat size (10 cm × 10 cm × 10 cm), have been built and launched.

Several problems, in particular carbonization and late time ablation, with a large fraction of the mass being exhausted at essentially thermal speeds, thus lowering specific impulse and efficiency, remain unresolved, notwithstanding decades of experimental research and numerical/analytical modeling in various countries.

Works by many authors have reviewed and analyzed APPTs[3,7–10], proposing mechanisms of operation and correlations between geometry, operating parameters and performance characteristics, and focusing in particular on breech-fed and side-fed configurations. More recent works have included other electrode configurations, in particular coaxial ones, in an effort to be more comprehensive in their analysis[8,9]. In the present paper such reviews are updated with the collection of data from recent literature and yet unpublished data. New correlations of experimental data are obtained, with special attention to the low-power devices developed in the last two decades.

An analysis of the type originally proposed by Guman in the 1970s[7,8], and subsequently reprised and further developed by the First Author three decades later[9,10], yields correlations that are particularly useful for design purposes, like the generally accepted linear dependence of impulse bit on discharge energy. It is questionable, though, whether such results are valid over a wide energy range, in particular at the very low end of the discharge energy spectrum. For such low energies a general degradation of performance is observed, with values of the thrust/energy ratio sensibly lower than those observed at higher energy levels. This is especially true for breech-fed configurations, even if some experimental investigations seem rather to suggest a considerable data spread, with performance (impulse bit and specific impulse) strongly dependent on thruster design, and in particular on electrode geometry[10–13].

The issues discussed above are addressed in the present paper by new interpolations, using different functions or the same simple linear functions, but applied to data within limited energy ranges and extending the analysis to coaxial configurations, which seem especially promising at low discharge energies. Insights on APPT operation mechanisms are also sought from physical considerations. The aim is to develop a new set of formulas that will be useful for the design of high-efficiency configurations for low-power APPT propulsion systems, which are going to find increasingly wider application in the growing market of micro, nano and pico-satellites[14–18].

II. APPT System Characteristics

Despite being one of the simplest EP systems, APPTs' operational behavior is highly sensitive to any changes in the thruster characteristics. Therefore, it is crucial to take into account the design of each subsystem to optimize the thruster to its specific mission[15].

As already has been said, APPTs are usually classified by the propellant and electrode geometric configuration (generally described as Breech-fed, Side-fed and Coaxial), that basically defines the way that the propellant is exposed to the discharge. But, beyond this, there are other critical characteristics that can alter widely the behavior of the APPTs, like the geometry of electrodes, propellant feed methods, chemical augmentation of the propellant, power system configuration, etc [3]. Saying this, the next sections will be devoted to clarifying the concepts around the main subsystems of this thruster.

A. Electrodes

When it is considering the change in performance due to the electrodes, two main characteristics must be taken into account: its geometry and material.

1. *Geometry*

With the initiative of Palumbo and Guman, in the late 1970s, many experiments were conducted studying the variation of parameters such as the aspect ratio of the area, spacing between electrodes and flare angle, leading each of them to obtain important design tendencies[19,20]. Some of the most remarkable are: (1) As the electrode spacing is increased the thrust to power ratio tends to decrease while specific impulse tends to increase. In the other hand, efficiency was crescent until approximately $3in$ of separation and decreased for bigger values; (2) When the exposed propellant area was increased,*e.g.* increasing of mass loss, (holding all other parameters constant) the efficiency tended to fall along specific impulse; (3) Specific thrust and specific impulse tended to fall as the electrode length was increased.

Another way to improve, or at least change, the performance of APPTs is the consideration of flare angles, *e.g.*the angles between the electrodes. Many previous experiments[19,20] reported substantial gains in performance, in both side and breech fed configurations, when flare angle were increased. The optimal angle were found to be around 20 degrees, showing an increasing in impulse bit, thrust to power ratio, specific impulse and thus also in efficiency.

In the designing of electrodes it is also important to consider different shapes, beyond the traditional rectangular configuration. A widely used one is the tongue shape. As shown by Schonherr, et al., from the University of Stuttgart[21] the utilization of a tongue shaped electrode results in the increasing of specific impulse, impulse bit and efficiency.

When is considered the coaxial electrode symmetry, it is important to note that substantially less amount of experimental work have been done in the studying exclusively the influence in performance of changing the electrode main characteristics. Nevertheless, it is possible to point out some main results that can show its behavior trends. Edamitsu, *et al.*,[22] from Osaka University, between many others[23−25] performed several experiments testing mainly the influence of the cavity length and diameter. Thereby, some remarkable design trends were observed: (1) The thrust efficiency is decreased mainly by the transmission losses if the cavity length (distance between electrodes) is short and mainly by the acceleration losses if the cavity length is long; (2) The reduction of the cavity diameter decrease transmission energy losses due to the high plasma resistance and cavity pressure; (3) because of the 1^{st} remark, exist an optimal cavity length. This optimum decreases with the direct current resistance of the discharge circuit; (4) While the cavity diameter is increased, the specific impulse (together with thrust efficiency) increases and the impulse bit (together with mass shot) decreases.

Due to the size of the exposed propellant area, in general the acceleration of the coaxial APPT is mostly due to thermal expansion. If one desires to design such thruster with majority of electromagnetic acceleration, it is necessary to decrease its discharge area [22]. Many other works has been developed to better understand the real behavior of geometry changes, but due to its inherent great complexity, until today they are poorly understand. As pointed by Rezaeiha [26], from Sharif University of Technology, there is a necessity for the investigation in more depth of the dependence of performance on geometry, specially in cases of miniaturization, when secondary effects such as boundary viscous losses might become important.

2. Material

Mainly five materials have been considered for the construction of the electrodes[26]: cooper, brass, molybdenum, aluminum, stainless steel and cooper-tungsten alloy. Still, cooper is the most traditional and have been used aboard several flight model APPTs, thus usually designers keep relying on this choice, once that characteristics do not change dramatically from one material to another. Nevertheless, many effort have been done to determine the best metal to be used.

Kawahara, *et al.*,[27] at Tokyo Metropolitan Institute of Technology demonstrated experimentally that molybdenum presents a significant better performance than brass, including the diminishing of electrode erosion, bigger melting temperature, and increasing of specific impulse. Guarducci, *et al.*, from University of Southampton and Mars Space Ltd., proposes the using of a cooper-tungsten alloy for the electrodes construction[16]. As reported, the selection of this alloy was mainly due to the reduction of erosion rates and a better thermal capabilities when compared to pure cooper.

B. Propellant

The quest for better solid propellants is one of the most long and profound of the APPT research history. Many authors, including again Palumbo and Guman[20], from Fairchild, and Pencil and Kamhawi from NASA GRC[28], published extensive works analyzing the performance parameters of many polymers but still, after almost 40 years, Polytetrafluoroethylene, the Teflon®, is one of the most efficient and reliable.

In the first mentioned work the authors examined several unusual plastics in order to analyze its capabilities as propellant materials. The main parameters analyzed were specific thrust, specific impulse and efficiency. The polymers evaluated included: Celcon®, Halar®, Tefzel®, Halon® and Teflon® augmented with *LiOH*. The results again sustained the position of nominal Teflon®, *i.e.*, no other plastic produced relevant levels of specific thrust and impulse that would justify the changing from a traditional propellant[26].

In contrast, Pencil and Kamhawi evaluated in their work the advantages of using Teflon® with different densities, with porosity or impregnated with carbon heavy particles, in order increase its performance.

The parameters measured included discharge current characteristics, ablation rates, steady-state thrust and impulse bit.

Some conclusions of this work can be pointed out: (1) porosity increases ablation rates, but not the thrust levels, *i.e.*, the porosity do not contribute to the performance; (2) The carbon impregnated Teflon® presented sightly better levels of specific impulse and efficiency when compared with the nominal one; (3) High density and nominal Teflon® presented the higher levels of electromagnetic component in thrust.

It is possible to identify several further studies that evaluated alternate propellant strategies and materials. Saito, *et al.*, from the University of Tokyo[29] proposed the using of powdered propellant instead of the traditional bar. This method presented huge levels of mass ablation per shot in consequence of the propellant low bond energy. Due to the low performance levels and the necessity of implementation of motorized moving parts, this strategy so far it is not interesting. Paccanni and Chiariotti, from the University of Rome, *Sapienza*,[30] studied three different polymers in their ablative MPD thruster: Hyflon®, Polyethylene (PE), Halar® and, for comparison, Teflon®.

The measured parameters included ablated mass, jet velocity, impulse bit and current characteristics. The results of this study pointed that the higher levels of ablated mass and impulse bit were produced by the Teflon®, while PE produced bigger exhaust velocities. The overall performance of the propellants was similar, but the Teflon® continued to present more advantages for the application in APPTs.

C. Ignition System

One of the most critical subsystem of the APPTs is the ignition system, once that the operation of the entire thruster depends on its correct behavior. It has the role of performing an initial plasma discharge on the surface of the propellant bar so that sufficient material is evaporated to sustain the main current discharge[3]. To date, the most used method of ignition is based on the spark plug, that generates a low energy discharge on the surface of a semiconductor material to produce the spark. However, this system presents a series of problems, including, reduced lifetime, due to erosion and carbon contamination, and reduced reliability.

Two main alternatives are found in the literature. The first one is presented by Kushari, from Indian Institute of Technology Kandur, and it is called "auto-initiated PPT"[31]. This system is based on applying direct high voltage to initiate the discharge. The elimination of the spark plug could increase significantly the lifetime of the thruster.

The second approach is to use laser to ablate the propellant, described by Horisawa, *et al.*, [32]. In this proposed system, the laser beam is shot on the face of the propellant bar, ablating a portion of material and ionize it. With this, the main discharge takes place, forming more plasma and performing the acceleration. The laser-assisted ignition system presents higher reliability and lifetime, once that the laser applied is a commercial optical electronic equipment, in contrast with the spark plug that it is usually constructed together with the thruster.

Still, there are other secondary alternatives for discharge initiation[26] that were not described, like the thermionic emission and thermal-field emission.

D. Power System

The power subsystem of the APPT is usually composed by two main parts: the PPU (Power Processing Unit) and the capacitor bank.

The main function of the PPU is to charge up (or discharge) the capacitor bank with the necessary energy in the required time interval. Usually this system receives a low voltage (ranging from $+8V$ to $+35V$) supply from the spacecraft and converts it with the help of a DC-DC converter (usually a flyback) for levels in the kV magnitude. This high voltage is redirected to the capacitors that stores it and finally provide the main discharge inside chamber.

Since the PPU effectively controls the energy level in the capacitors, usually it has a digital system that perform the interface and control of the thruster[33]. Usually the ignition and main discharge are generated frin different power systems, and sometimes it is not even necessary to have a capacitor bank for the ignition system.

Lim, *et al.*, from the Korea Advanced Institute of Science and Technology, proposed the PPU presented in figure 2, for the using in APPT module of the satellite STSAT-2, launched in 2009. This model was designed to receive a voltage of $+28V$ from the spacecraft and then converts it to $1.5kV$ to charge up the $1.6F$ capacitors in the period of $20ms$.

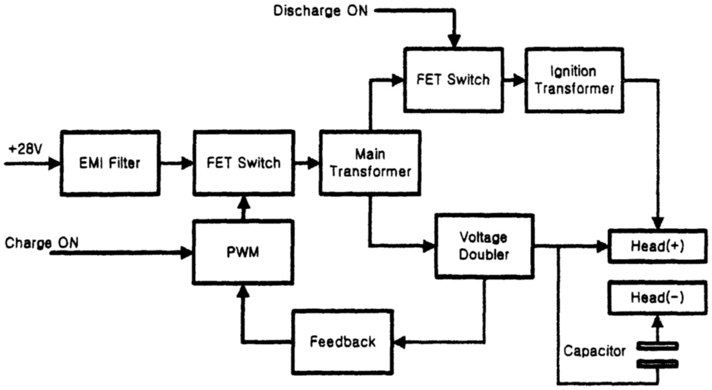


Figure 2. General design of a PPU[33].

Takegahara, *et al.*, reports that their PPU design includes two power supplies (one for the capacitor bank and another for the ignition system), a command and telemetry module and are designed to charge up the capacitors of $2\mu F$, converting voltage from $+12V$ to $1.5kV$ [34].

There are an infinite number of possible ways to design and use the PPUs and capacitor banks, however they comprise a big part of the APPT weight and the direction of optimization of this subsystem is toward the obtaining of a lighter overall weight of the system. Usual densities for power systems are around $100W/kg$[9].

III. Basic Physics

The physical understanding of mass acceleration in an APPT is not trivial. It encompasses a number of complex phenomena that results in the process of the ablation, ionization and acceleration of the propellant. Due to this complexity, until today there are no consistent models of the complete physical behavior of the APPTs. As stated in the literature[35], the main problem in obtaining these models is the fundamental lack of understanding of the complex thermal-electric energy transfer from the discharge to the propellant.

Nevertheless, even with these difficulties, it is possible to derive simple relations that allow us to understand the fundamental mechanics of the system, using previous experimental data, and therefore conduct preliminary design calculations . In detailed design phase it is usually required to use computational (MHD and PIC methods) tools to perform optimization of system configuration[36,37].

A. Design Laws

As previously mentioned, it is possible to achieve simple laws that allows us to perform the preliminary design of APPTs based only on technical and experimental data [8,9]. These laws have been widely used by the research groups since the late 1960s for the general scaling of the main subsystems. They will give basis for the semi-empirical laws explored in the next sections. Saying this, consider an APPT that performs discharges with a frequency f, that the ejection of mass m in each pulse produces the impulse bit, I_{bit}, and that the energy released by the capacitor bank per cycle is given by E. So the equivalent generated steady-state thrust, mass flux and power delivery are given by the three basic relations,

$$T = fI_{bit} \tag{1}$$

$$\dot{m} = fm \tag{2}$$

$$P = fE \tag{3}$$

It is important to note that the most commonly used units for I_{bit} is μN-s, f is Hz, E is J and for m is kg. It is also important to realize that with the derivation of the last equations it became possible to transform discrete pulsed parameters in steady-state variables, allowing us to apply the general propulsion equations. With this, it is possible to define two important parameters for propulsion, the specific impulse, I_{sp}, and the specific thrust I_t.

They are respectively defined as,

$$I_{sp} = \frac{T}{\dot{m}g} = \frac{I_{bit}}{mg} \tag{4}$$

$$I_t = \frac{T}{P} = \frac{I_{bit}}{E} \tag{5}$$

Having this, it is straightforward to define another important parameter, the thrust efficiency, η_t, by

$$\eta_t = \frac{T^2}{2\dot{m}P} = \frac{I_{bit}^2}{2mE} \tag{6}$$

Thereby, in the possession of these six basic equations it is possible now that measured data is correctly interpreted. Considering just a few performance parameters, it is possible that every experimental thruster is properly compared to each other, allowing the designer to have tools to begin a preliminary configuration drawing. In fact, the described relations does not limit one to use just the described variables, permitting instead the coupling of several systemic parameters as shown by Coletti and Gessini[9,15].

B. Operation and Analytic Considerations

The basic operation of the APPT is usually divided in three main parts, the energy storage, ignition and main discharge.

Firstly, the PPU (Power Processing Unit) redirects the incoming energy from the spacecraft to the capacitor bank until it has sufficient energy for the main discharge process (usually a secondary capacitor bank is also charged for the ignition discharge).

Secondly, the igniter plug is activated, ablating and ionizing a small quantity of material inside the discharge chamber. Finally, the capacitor bank is connected to the electrodes and the main discharge occurs, generating a high current discharge on the surface of the propellant bar, thus producing ablation of the material and its ionization.

The resultant plasma is highly complex and have several species in its composition resulting from the breaking of the propellant long molecule(usually Polytetrafluoroethylene, commercially known as Teflon®). Due to the action of the Lorentz force and thermal gas expansion thrust is generated. Saying this, it is possible define, for a given APPT, the resultant thrust as the sum,

$$T = T_L + T_{Th} \tag{7}$$

Where T_L is the thrust generated by the Lorentz force and T_{Th} by the gas expansion. Each of the right-hand side terms of the last equation must be modeled according to the geometry and configuration of a given thruster.

Even so, for the sake of general understanding of the physics of APPTs, we can describe the most common model for simple rectangular configuration, idealizing the discharge geometry as a simple flat sheet. Saying this, from magnetic pressure the electromagnetic portion of impulse can be modeled as[9,35,38],

$$I_L = \frac{\mu_0 h}{2w} \int_0^\tau i(t)^2 dt \tag{8}$$

Where the h is the height of the current sheet and w is its width. It is common to define the integration over the discharge period τ as

$$\Psi = \int_0^\tau i(t)^2 dt \tag{9}$$

Ψ is called the *current parameter*.

Robert Vondra, from MIT, derived in the late 1970s, an approximately expression for the thermal gas expansion term[38]. Considering the mass loss m_α and characteristic thermal velocity c_α of each species, the gas expansion impulse can be modeled as,

$$I_{th} = \int_A dA \int_0^\tau nm\langle v_i v_j\rangle dt \approx \sum_\alpha m_\alpha c_\alpha \tag{10}$$

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

$$I_{bit} = \frac{\mu_0 h}{2w}\Psi + \sum_\alpha m_\alpha c_\alpha \tag{11}$$

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

$$I_{bit} = \frac{\mu_0 h}{2w}\Psi + m\bar{c} \tag{12}$$

The simplified theoretical model for specific impulse and the thrust efficiency thus becomes respectively,

$$I_{sp} = \frac{I_L}{mg} + \frac{\bar{c}}{g} \tag{13}$$

$$\eta_t = g\frac{I_{bit} I_{sp}}{2E} = \frac{I_L}{2mE} + \frac{\bar{c} I_L}{E} + \frac{m\bar{c}}{2E} \tag{14}$$

It is important to note that the ablated mass m must have some kind of dependence on the discharge energy E. In idealistic models developed in the 1970s for breech fed APPTs there was found a *linear* relation between them[38], thus sustaining the ideas of semi-empirical relations largely used until nowadays.

However it is necessary to mind that with the appearance of new high efficient technologies and large variation on the APPTs geometries, the simplistic models start to deviate grossly from the obtained experimental data and thus the traditional semi empirical laws does not continue to be an reasonable approach to design. New statistical relations and interpolation functions must be obtained that can reflect the behavior of the modern APPTs, thus directing design process to optimized configurations.

IV. Semi-Empirical Relations

William J. Guman, from the Fairchild Republic Company, in the end of the 1960s, facing the great complexity of modeling the ablation process in the APPTs developed the so-called semi-empirical relations for the experimental data [3,7](for breech and side fed configurations).

This was an attempt to simplify the engineering design process creating functions that could reflect the variation of experimental data parameters without the necessity of a complete physical model. The relations developed focused mainly in 4 parameters: (1) discharge energy, E; (2) impulse bit, I_{bit}; (3) area of propellant exposed to the discharge, A_p; (4) specific impulse, I_{sp}. Thus, in section the semi-empirical relation will be evaluated taking into account the modern experimental data from breech fed, side fed and coaxial geometries. New interpolation will be made to show new possibilities for experimental data correlation and questioning of the validity of the relations proposed 40 years ago.

The first relation reflects the expressions derived in the last session, where a linear dependence of ablated mass with discharge energy could be inferred if a simplistic model were assumed. Thus, if we consider the specific thrust, I_t, as the constant of proportionality, the relation can be expressed as,

$$I_{bit} = I_t E \tag{15}$$

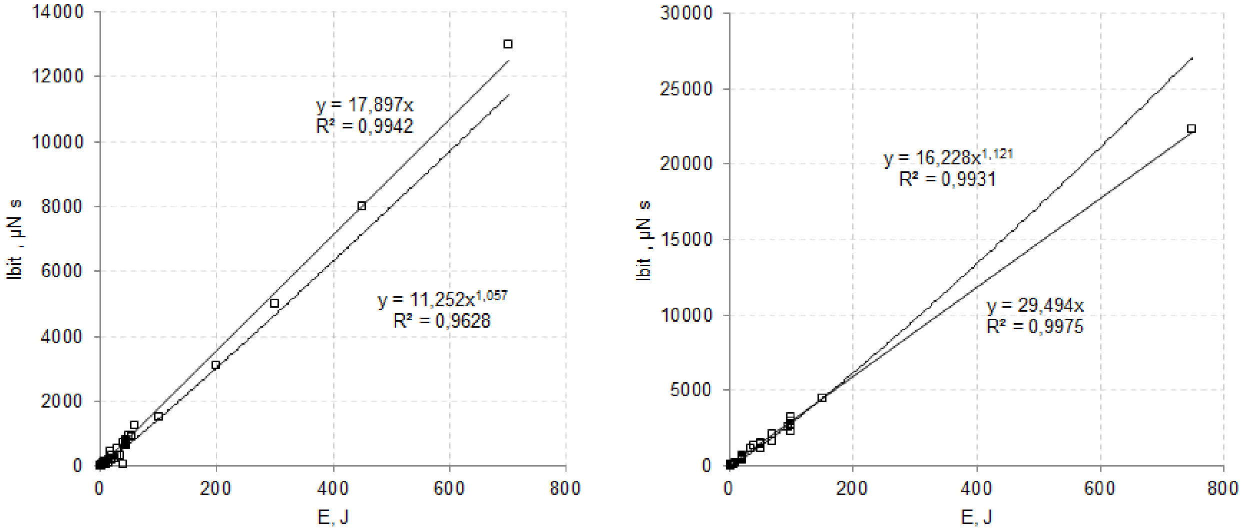
In order to evaluate the "linearity" of the modern experimental data, another expression will be considered for interpolation, the power law,

$$I_{bit} = \alpha E^\beta \tag{16}$$

Where the β is the "proportionality parameter", an indicator of how much linear is the data. If β approach the unity the data approach the linear behavior.

Gathering the experimental data from several works and performing the interpolation with both two last equations it can be shown that the linear behavior is quite reasonable if it is considered the whole energy regime from 0 to $750J$(figure 3). It is important to note that available data with discharge energies around $750J$ only comprises the breech and side fed geometries.

It can be observed that in the case of breech fed, in the large energy interval, the linear assumption is quite reasonable without major losses, once that in this case $\beta \approx 1.05$ and the coefficient of determination, R^2, of the linear approach is higher than of the power law.



(a) Breech-fed [14,19,28,34,39–48]

(b) Side-fed[3,16,38,49–55]

Figure 3. Semi-empirical relation of I_{bit} and E, 0-750J interval.

In the case of side fed geometry both functions presented similar R^2, but β increased to $\beta \approx 1.12$ revealing a data trend approaching a curved pattern. Similarly the side fed also does not present large data scatter.

In the next step, let us consider the energy interval limited to 100J (figure 4). Clearly, in this this case all geometries, now including coaxial, presents larger data scatter. Another interesting aspect is that as we decrease the interval of energy, *i.e.* approach the low energy regime, the inclination of the linear interpolation also decreases, indicating that in all cases the data presents a trend to be curved with lesser inclination at low energies.

The breech fed configuration continues to present at this interval a behavior that approximate the linear relation, $\beta \approx 1.05$, however at this time R^2 has bigger value for the power law, indicating that the data is better fitted by a curved function (even if the curvature is small at this point).

In the case of side fed the curvature increased, $\beta \approx 1.14$, with R^2 much higher to the power law, indicating that the data set within this interval is better modeled by the suggested function.

When the coaxial geometry is observed, it is obvious that it presents a large data scatter when compered to the other configurations. This can be explained by the large amount of different design configurations that may vary the performance even in the same energy level. The parameter β had a low value in this case, $\beta \approx 1.02$, nevertheless the difference in the R^2 values indicates that the power law is much better to model this data set.

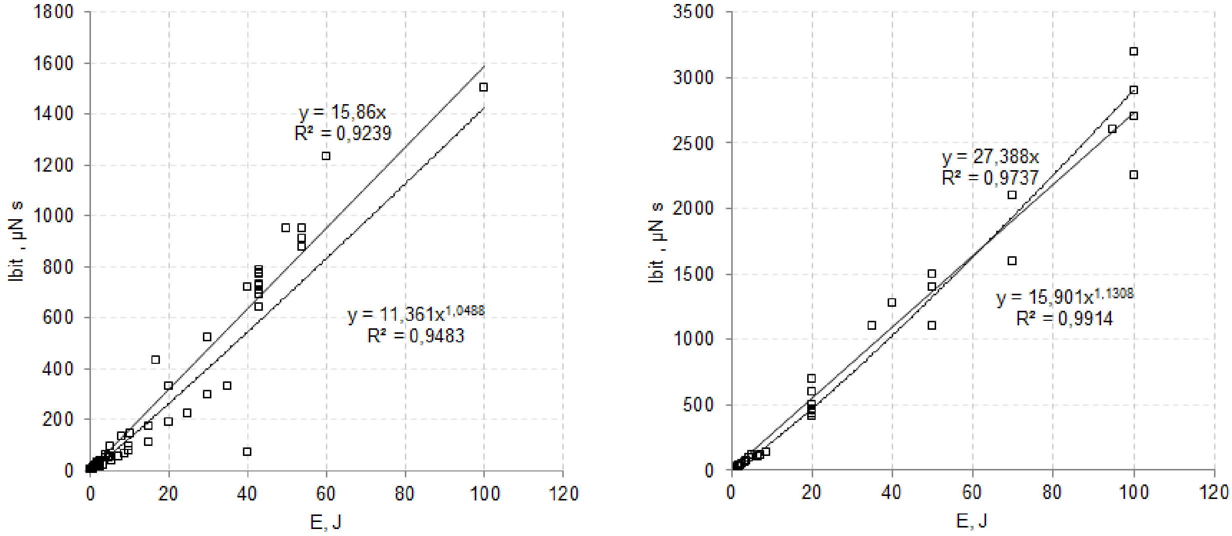
Now let us consider the *low power regime*, *i.e.* below 10J (figure 5). In this regime all the data sets presented large data scatter, with the exception of the side fed, that was the configuration that manage the most to maintain its linear behavior.

In this regime all thrusters present a degradation in their performance, suggesting mainly that at this regime the non-linearities that was neglected at the modeling phase start to be significant and small perturbations in the operation of the thruster change sensibly the dynamics of the ablation and acceleration [9,10]. This can confirmed by the interpretation of the curved behavior trend of data presented in this work.

The breech fed configuration in this case, presented a decreasing in the curvature denoted by β, but in any case R^2 sustained the power law as a better fitting function.

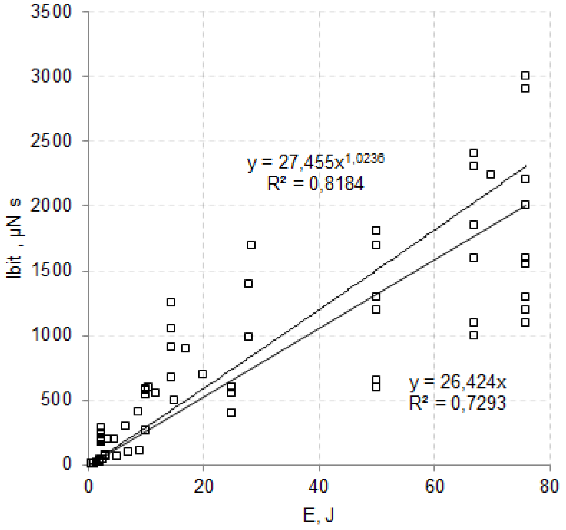
Anyhow, the decreasing in β does not indicate that the data became linear, once that the linear angular coefficient of the data set had decreased when considered to the other two intervals. The small amount of data available in this regime also compromise the verification of the data trend.

For the side fed it can be observed that the linearity inside this interval is verified, but anyhow again the linear angular coefficient decreased, confirming the data trend proposed.



(a) Breech-fed[14,19,28,34,39–48]

(b) Side-fed[16,38,49–53]



(c) Coaxial[18,22,25,56–61]

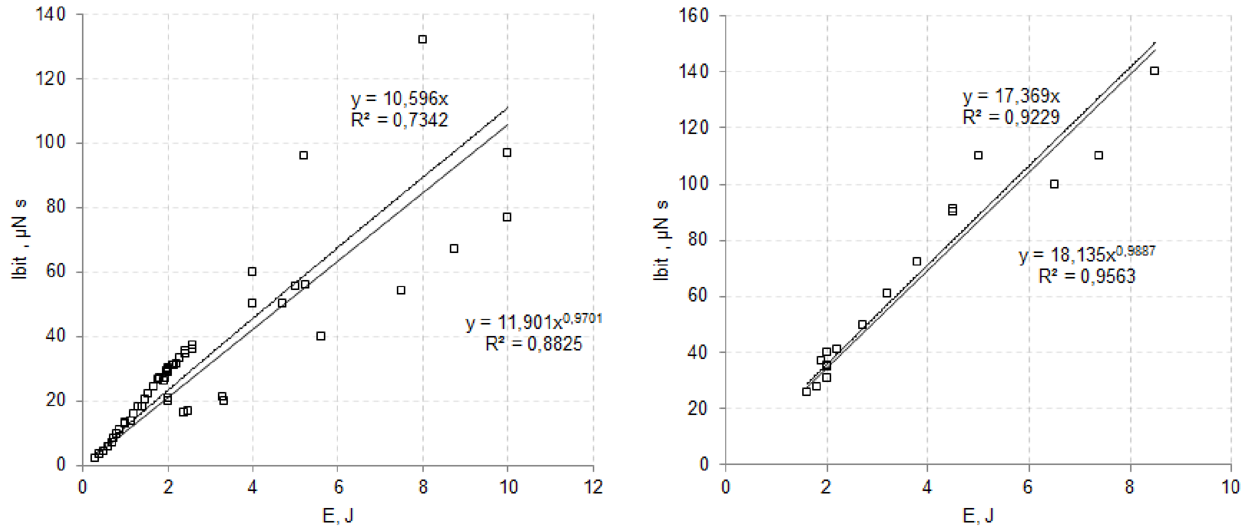
Figure 4. Semi-empirical relation of I_{bit} and E, 0-100J interval.

Finally for the low power coaxial geometry, a strong deviation from the linear behavior is observed. The proportionality parameter β achieved $\beta \approx 1.5$. R^2 confirmed again the validity of the approximation by the power law. Thus it is reasonable to accept this function as a model for designing of micro coaxial APPTs. Saying this the new equation becomes,

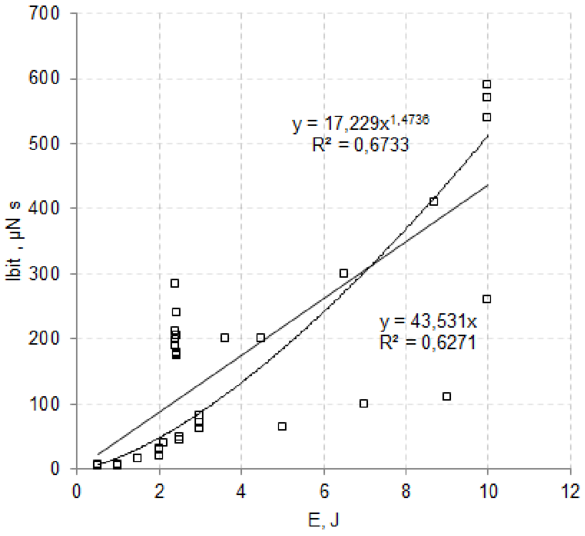
$$I_{bit} \approx 17.5E^{1.5} \tag{17}$$

The obtained relation will be used in the designing of a new set of micro APPTs that will be testes at the University of Brasilia (UnB) in the next months. The low power regime will be strongly explored by the program so that the semi-empirical correlations at this interval can be improved thus helping future development of this thrusters for small satellite missions.

For a final analysis on the semi-empirical correlations in this work, there is another important equation



(a) Breech-fed[14,28,34,39–44] (b) Side-fed[16,38,49]



(c) Coaxial[18,22,24,25,56–58]

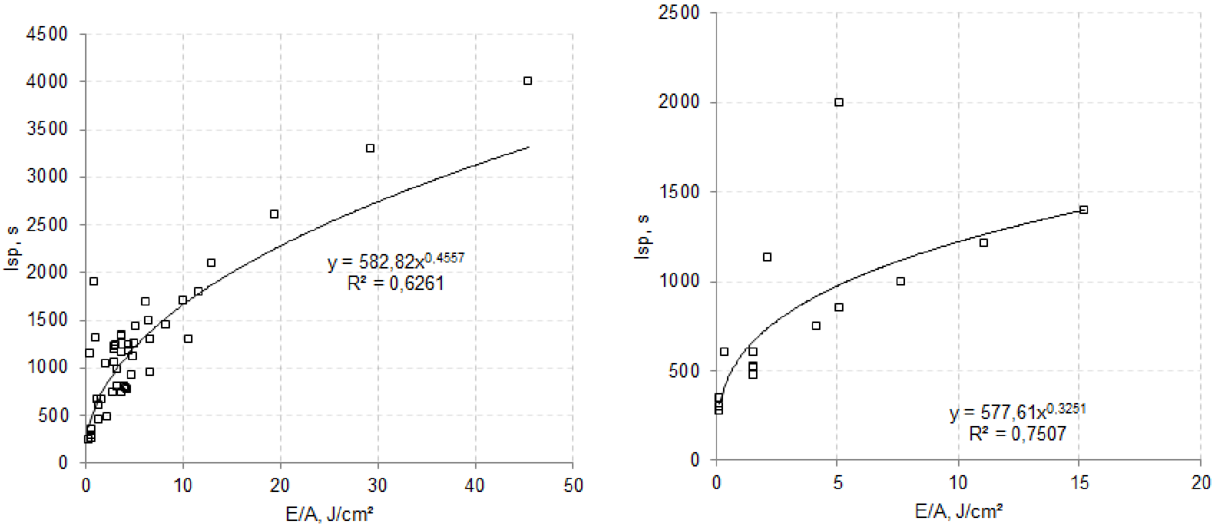
Figure 5. Semi-empirical relation of I_{bit} and E at the *low power regime*, 0-10J interval.

proposed by Guman in his paper, relating the specific impulse and the ratio E/A_p. Where A_p is the area exposed to the discharge. Usually A_p can be called also "wetted" propellant area. The relation can be expressed as,

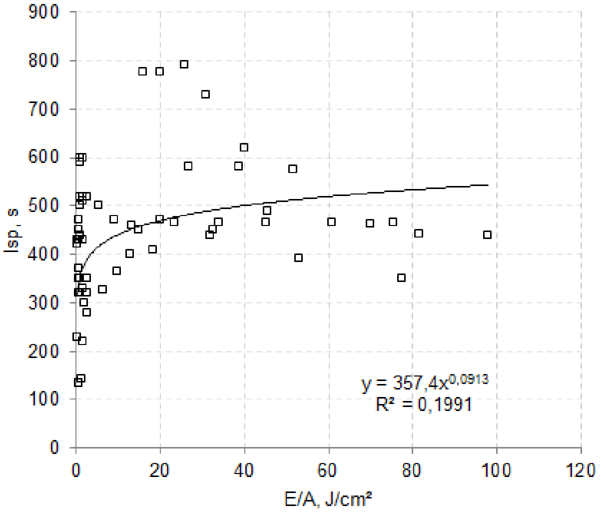
$$I_{sp} = k_1 \left(\frac{E}{A_p} \right)^{k_2} \tag{18}$$

In figure 6, experimental data is fitted by this equation. Clearly a large data scatter can be observed, this is due again to the appearance of several new kinds of technology comprising electrodes, circuitry, capacitors, beyond many others. These new resources end up generating thrusters with efficiency much higher of those in the near past.

With this, a general overview of the data patterns of APPT performance have been obtained. It is possible to oversee that if a dedicated research program is conducted to explore the semi-empirical relations,



(a) Breech-fed[19,34,39–48] (b) Side-fed [16,38,3,54,55]



(c) Coaxial[18,22,24,25,56,57,59]

Figure 6. Semi-empirical relation of I_{sp} and E/A_p at the 0-750J interval.

much better approximations can be obtained.

The Electric Propulsion Program of the University of Brasilia (UnB) will dedicate its next years to explore this relations in the low power regime, mainly working with the coaxial geometry, which still remains the APPT type that has been less explored and at the same time the one that presents higher performance prospects, when thrust is considered.

Beyond this, the University will also begin its program for the development of micro satellites. This gives a good opportunity for the team to develop micro APPTs to be applied in real space missions. At the same time, this gives good prospects for international collaboration envisioning the joint development of new APPT types.

V. General Remarks

A. APPT Research at Brazil

The Brazilian development of APPTs had occurred mainly at the Combustion and Propulsion Laboratory of the National Institute for Space Research (INPE). The research there began at 2002, with the development of micro coaxial APPTs. The activities envisioned the application of such thrusters at small satellites that ware being developed at other laboratories.

Recently the University of Brasilia (UnB) began efforts to accelerate the development of such thrusters mainly for the application onboard micro satellites that are being developed at the Space Systems Laboratory of the Aerospace Engineering department in collaboration with the Brazilian Space Agency (AEB).

With this, a new dedicated Electric Propulsion Laboratory is currently under implementation at the Aerospace Engineering department, inside the new Campus of the University, at the city of Gama. This new installation will be fully dedicated for the development of APPTs, Hollow Cathodes and micro Hall/Cusped thrusters.

What comprises the APPT development at this new Lab, the team will make efforts mainly for the exploration of the coaxial configuration running under low power discharge energies. We understand that this operational configuration had not been fully explored and their performance behavior still needs further characterization and explanation.

B. Micro Propulsion Market

As pointed out by Molina-Cabrera, *et al.*,[11] the spacecraft market is under a notable process of miniaturization. This has many important reasons but almost all of them revolves around the low budget strong requirement present in almost all modern space missions. With this, in the last years, big efforts have been conducted by the space industry for the development of new highly efficient miniaturized subsystems that allows the designers to envision smaller and cheaper satellites. Along this growing interest in the market of micro satellites, the APPTs are increasingly gaining space for application mainly for orbit correction and attitude control of these spacecrafts.

The main field for application of the APPTs currently is in the market of nano and pico satellites. These types of spacecraft usually have less than 10 kg of total mass and have been developed mainly for academic purposes. One of the famous nano satellite design is the CUBESAT, idealized in late 1990s, for the stimulation of the spacecraft design activities inside the Universities.

The market of the this kind of satellite is one of the fastest growing sectors in space market, and it is important to note that the inclusion of propulsion systems could play an important role for the improving of such programs. This can be emphasized by the fact that the Universities satellites usually, due to its strong budget restrictions, needs to use piggyback launch and their orbit are determined by the prime contractor. The altitude that they are usually placed is around 600-700 km and, with no propulsion system, the satellite has its lifetime critically shortened. Beyond that, the quality of the mission is also compromised due to the lack of an attitude control system.

The using of a propulsion system could solve either problem, and once that it is necessary to have simple, small, light and robust subsystems inside such satellites, the APPT shows to be one of the best options[15].

VI. Conclusion

This work has focused in providing a general overview of the main trends of the APPT technology development and demonstrating that it is possible to achieve improved semi empirical laws to perform the design of such systems, mainly at low power operation, where the data starts to deviate grossly from the prediction of the traditional relations. This demonstration was conducted basing on experimental data from many recent and former works.

At the first part we described the most relevant subsystems of the APPT, showing the advances in research in each field and what are the design trends of each one.

Then, in the second part, we made a brief discussion about general physical considerations and thrust modeling of the APPT. At this point we developed simple equations to give a general idea of the proportionality of each parameter and how they are expected to behave. The physical relations shown gave a basic foundation for the semi-empirical laws developed in the next section and, at the same time, the main reasons to contest their validity in our text.

With this, in the third section we exposed a big experimental data set relating the performance parameters of many different modern and pioneer APPTs, with three geometries: breech fed, side fed and coaxial. We used the traditional semi empirical laws to make interpolations, but it was demonstrated that, mainly in the case of the relation between impulse bit and discharge energy, the traditional linear relation was not sufficient anymore to perform the prediction of the data.

Therewith it was observed that the data set had trend of decreasing its "inclination" as the energy approach zero, or the low power regime, suggesting a curved pattern. With this, we proposed that a better modeling of the data could be achieved with the using of a different function, a power law.

Of course the lack of experimental data, at the low energy regime, limited the analysis and much better semi empirical relations can be obtained if a research program is dedicated to this. Thus, the Electric Propulsion program of the University of Brasilia (UnB), recently began a new research line for the construction and characterization of APPTs in order to improve the design relations at the low power regime.

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