An Overview of Essential Parameters on Ablative PPT Performance

IEPC-2011-341

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

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Abstract: **The purpose of this paper is to comprehensively review most of the significant works ever done worldwide to study the effects of essential parameters on PPT Performance and to analyze their effects. All the important works studying PPT performance are categorized by the parameter they have studied its effect on PPT performance and their works have been reviewed to analyze the influence of each parameter. The analysis leads to elucidate the effects of different geometrical parameters including aspect ratio, electrode width, electrode spacing, electrode shape, electrode length, electrode material, flare angle and also the effects of other parameters like propellant type, propellant temperature, Spark distance from propellant, pulse repetition frequency, discharge energy, connecting line between capacitor and thruster, and hood angle on PPT performance, as well. The analysis is mainly focused on rectangular breech-fed PPTs and side-fed PPTs and does not deal with co-axial PPTs. The results of the current analysis can be an invaluable assistance in PPT design and optimization procedure and helps the designer to develop a system with better performance characteristics.**

Nomenclature

α	=	flare angle
η	=	thruster efficiency
A_p	=	propellant area
A/R	=	aspect ratio
C	=	capacitance
c_e	=	exhaust velocity
E	=	discharge energy
Fr	=	thruster working frequency
h	=	electrode spacing
i	=	discharge current
I_{bit}	=	impulse bit
I_{sp}	=	specific impulse
L	=	electrode length
m_{bit}	=	mass bit per shot
P	=	input power
t	=	time

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T	=	thrust
T_p	=	propellant temperature
V_0	=	capacitor voltage
w	=	electrode width

I. Introduction

PULSED plasma thruster (PPT) is one of the most promising space propulsion systems to perform various propulsive tasks, including translational maneuvers and orbital maneuvers, on micro- and nano-satellites as it offers many advantages over other types of thrusters from the same league. Some of its advantages are listed below[1]. PPT can produce impulse bits in a wide range from very low µN-s up to mN-s with a specific impulse around 1000 s or even more.

1) Zero warm-up time, zero standby power.
2) Inert and fail-safe—no unpowered torques or forces.
3) Scaleable to performance requirements.
4) Usable on spinning or three-axis stabilized satellites.
5) Solid propellant advantages: no tankage, feedlines, seals, mechanical valves, easily measured propellant consumption, zero-g, cryogenic, vacuum compatible, noncorrosive, nontoxic, long shelf life, not affected by rapid temperature changes, or not affected by variable high ‘‘g’’ loads.
6) Discreet impulse bits compatible with digital logic.
7) Variable thrust level.
8) Performance compatible with attitude control and stationkeeping requirements.
9) Operation at large variation in environmental temperature.
10) Thrust vector control capability.

As a result of the many advantages that PPT offers, it was the first electric propulsion system used in a space mission back in 1964. From that time, many experimental laboratory studies have been conducted on PPTs to clarify the complex physics which lead to production of impulse bits in the thruster. Comprehending the thruster physics assists in getting to know the essential parameters effective on that. Therefore, those effective parameters maybe used to control the thruster physics and to optimize it.

Many studies have been carried out worldwide, studying the effects of many parameters on PPT performance. Each has tried to clarify the effects of one or two parameters on PPT impulse bit, specific impulse, and other performance characteristics. According to the available issued papers, one of the first laboratory studies on solid propellant PPTs (both rectangular and co-axial) was done by Guman[2] in 1968 when he studied the effects of discharge energy and electrode length on PPT specific thrust and specific impulse.

Afterwards, numerous studies were done to elucidate the effects of various parameters, geometrical and non-geometrical, on PPT performance characteristics (including impulse bit, specific impulse, mass bit per shot, exhaust velocity, thruster efficiency). PPT geometrical parameters include electrode width and length, electrode spacing (distance between electrodes), electrode shape, angle between electrodes (flare angle), aspect ratio (ratio between electrode spacing and electrode width), distance between ignitor plug arc and propellant surface, propellant face area, and type of propellant feeding (breech-fed or side-fed). Besides, some of non-geometrical parameters are listed as: discharge energy, propellant material, propellant temperature, electrode material, capacitor type and discharge behavior, capacitance, operating voltage, ignitor plug discharge behavior, thruster working frequency, thruster input power.

Considering all the works ever done, it was felt that at this time, it is a must to have an overview on all the significant works which have studied the effects of essential parameters on PPT performance. Furthermore, an analysis also has been done to investigate the results of aforementioned studies in order to elaborate the effects of the studied parameter on PPT performance characteristics. The present paper explains the results of previously mentioned overview and analysis and authors hope that it would be an appropriate assistance to those who intend to design and optimize pulsed plasma thruster. The current study is mainly focused on rectangular PPTs, both breech-fed and side-fed, and barely discusses the co-axial PPTs.

II. Influential parameters on PPT performance

A PPT is made up of various parts but at the same time has a simple mechanical structure. It almost has no moving parts, thus, giving a high reliability to the system. However, it has a sophisticated physics which is a function of many different factors. Listed below in Table 1 is a summary of the most essential factors which are effective on PPT performance.

Table 1 Influential factors on PPT performance

Geometrical parameters	Electrodes' length/width/thickness
	Electrodes spacing
	Flare angle (α)
	Electrode shape (rectangular/tongue)
	Aspect ratio (h/w)
Capacitor characteristics	Internal resistance/inductance
	Discharge behavior
Propellant	Propellant face area
	Propellant type (PTFE or else)
	Propellant temperature
Ignitor plug	Type
	Distance between spark and propellant face
	Spark energy
	Plug discharge behavior
Type of propellant feeding (breech-fed or side-fed)	
Electrodes' material (conductivity and erosion resistance)	
Discharge energy (a function of capacitance and maximum voltage)	
Input power (a function of discharge energy and thruster working frequency)	

A. Propellant Material

Almost all the research and development ever done on ablative PPTs considered PTFE as the propellant of choice, but there are a few studies which have investigated the possibility of using other propellant for APPT. Palumbo and Guman[3] at Fairchild Industries replaced Teflon by four different thermoplastics including Celcon, Halar, Tefzel, and unsintered Halon and they also tried Teflon seeded with 10% and 30% LiOH and InBr in an evaluation of alternative propellant.

The results of their research proved that none of the alternate plastics produced a thrust/power ratio comparable to Teflon and, with the exception of Tefzel; specific impulses were in the same neighborhood as that of Teflon. Halar was char forming, which resulted in a noticeable decrease in impulse bit amplitude as a function of operating time during the performance test. The surface of this plastic exposed to the discharge was completely black after approximately 1000 discharges. The replacement of the two fluorine atoms by two hydrogen atoms in Tefzel, as opposed to Teflon, is probably the reason for the high specific impulse measured since the molecular weight of the resulting plasma is conceivably lower. The presence of hydrogen in Celcon is probably offset by the addition of an oxygen atom. Results of performance testing with these thermoplastics taken from Ref. 3 are presented in Table 2.[3] In addition, as evidenced by the data reported by Ref. 3, no significant increase in performance was also realized by seeding Teflon with InBr. They also reported that it was not possible to obtain an overall performance evaluation for the LiOH seeded samples because a significant monotonic decrease in the impulse bit was observed during testing as a result of deposition of some high-resistance compound on the electrodes. Decrease in peak current were also observed during the tests.[3] A summary of the data taken from Ref. 3, using the InBr seeded samples as well as a test in which pure Teflon was used is presented in Table 3.[3]

Table 3 results of tests for various plastics[3]

Propellant	Teflon	Celcon	Halar	Tefzel	Halon
E (J)	454	436	-	416	381
T/P (mN/kW)	21.07	17.91	-	16.05	17.47
Isp (s)	5170	5500	-	8410	5100
η (%)	53.4	48.3	Charred	66.2	48.7

Table 2 results of tests for InBr / Teflon[3]

Propellant	100% Teflon	10% InBr3 / 90%Teflon	30% InBr3 / 70%Teflon
E (J)	390	387	400
T/P (mN/kW)	20.14	20.45	19.47
Isp (s)	4610	4500	4901
η (%)	45.4	45.1	38.3

Additionally, Pencil and Kamhawi[4] at NASA GRC also investigated various density Teflon and carbon-impregnated Teflon as PTFE propellant and compared the performance results with nominal Teflon. The results presented in Table 4 showed that nominal Teflon has the best performance characteristics among all and no improvement was made by the alternative propellant.[4] Following this further, some studies[5] have been done by Saito from The University of Tokyo on using powdered Teflon as the propellant for APPT instead of solid Teflon but the results show no performance improvement.

Table 4 results of tests for nominal, carbon-impregnated, and various densities of Teflon[4]

Propellant	Energy (J)	m_{bit} (μg/pulse)	I_{bit} (continuous shot) (μN-s)	I_{sp} (s)	η (%)
Nominal Teflon	20	32	349.19	1048.7	8.45
High-density Teflon	20	30.78	326.52	1012.6	7.58
500-μm porous Teflon	20	34.12	330.27	1061.1	6.31
2% - Carbon Teflon	20	24.2	239.43	N/A	N/A

In the final analysis and based on the research presented above, nominal solid Teflon is the propellant of choice for Ablative PPT so far and no alternative solid propellant with better performance has ever been investigated. Because of the fact that we narrowed our research on ablative PPTs, other alternatives including liquid and gaseous propellants were excluded; although there have been numerous studies conducted on liquid and gas propellants as alternatives for Teflon, but none of them has ever been flight tested.

B. Propellant Temperature

A research conducted by Spanjers et al.[6] at AFRL demonstrated one possible method of increasing the PPT propellant efficiency. They established a correlation between decreased propellant temperature and increased propellant efficiency by measuring the PPT thrust, propellant consumption, and propellant temperature while varying the power level, duration of the experimental run, and total propellant mass. The method was demonstrated by performance measurements at 60 W and 5 W, which show a 25% increase in thrust efficiency and no effect on thrust, while the propellant temperature decreases from 135 to 42°C. It also showed that influences that act to increase the propellant temperature in the PPT will also act to increase the propellant consumption rate. Moreover, larger increases in the efficiency may be realized on-orbit where ambient temperature is commonly sub zero. Although the satellite operating temperature depends on the satellite design and is usually kept above zero to prevent circuits from freezing but PPT is usually mounted on the outer surface of the satellites and is more probably subject to the ambient temperature; considering the fact that, with the exception of electronics, PPT does not need special temperature considerations and can operate in any temperature conditions. Additionally, significant improvements are attainable in the propellant efficiency by designing the PPT to reduce the propellant temperature.

Equally important, the mentioned research also showed that the propellant inefficiency in the PPT is a severe limitation on the thrust efficiency, with between 80 and 90% of the total propellant expelled at low velocity in the form of neutral gas and macro particles.

C. Electrode Characteristics

Dimensions of the PPT electrodes are of huge importance to its performance. Width (w), length (L), electrode spacing (h), aspect ratio (h/w), flare angle (α), and electrode shape are geometrical parameters of PPT electrodes. Electrode material is also of importance as it determines the conductivity of the path as well as its erosion resistance.

1. Electrode Width, Spacing, Aspect Ratio, and Propellant Face

Numerous studies have been done to investigate the effects of electrode width (w), electrode spacing (h), aspect ratio (h/w), and propellant face (A_p) on PPT performance as they are among the most significant parameters to drive a PPT design although still further study is needed in this case. Palumbo and Guman[3] at Fairchild Industries studied electrode spacings of 6.6, 7.62, and 10.16 cm with corresponding ratios of E/A_p equal to 8.56, 9.59, and 8.80 J/cm^2. Their data also indicated a monotonic trend toward lower thrust/power ratio and higher specific impulse as the electrode spacing is increased. Efficiency, however, is highest at the 7.62-cm spacing and falls off rapidly from 23.6% to 19.2% while the thrust/power ratio (T/P) increases from 37.52 mN/kW to 38.76 mN/kW when h is decreased to 6.60 cm. The increase in T/P afforded by decreasing h is, therefore, accompanied by a much stronger drop in specific impulse. It was also observed, by monitoring the response of a Rogowski coil which measured total discharge current, that as h decreased the discharge became more oscillatory, and that even though E/Ap was approximately the same in all tests, a larger amount of mass per discharge was obtained as h was decreased. Figure 1

shows the change in performance of side-fed configuration as function of electrode spacing with an electrode included angle of 20 degree.[3]
Additionally, Ref. 3 experimentation at the 10.16 cm spacing included two tests in which the propellant area was increased. These tests were performed to explore further the effect of introducing additional mass into the discharge, all other parameters remaining constant. In the first test, the propellant area was increased from 53.4 sq cm to 66.7 sq cm. This resulted in an increase in mass per discharge from 0.849 to 1.158 mg, accompanied by an increase in T/P from 28.67 to 33.03 mN/kW with decreases in Isp and η to 1060 s at 18.2%. Further increasing the propellant area to 77.42 sq cm increased the mass per discharge to 1.54 mg and thrust/power ratio to 34.85 mN/kW with decreases in Isp and η to 1060 s at 18.2%. These tests further suggest that the introduction of more propellant mass, all other parameters held constant, reduces the efficiency of this device at a given discharge energy.[3]

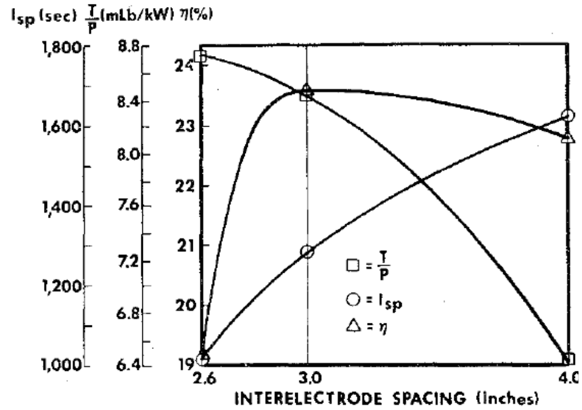

Figure 1. Thruster performance of side-fed PPT at different electrode spacing with an electrode included angle of 20 degree [3]

In addition, Pottinger and Scharlemann [7] at Austrian Research Center investigated the effect of aspect ratio on PPT performance by changing electrode width and spacing. As can be seen in Fig. 2, the extent and fashion in which the performance changes depends not simply on the aspect ratio but on how the aspect ratio change is obtained. It cannot simply be explained by the changing energy per unit area. Available semi-empirical equations[8] between energy per unit mass and performance fail to predict such a correlation. Points A and B for example correspond to equal propellant surface area, hence according to semi-empirical relationships for thruster performance the I_{bit} should also be equal, clearly this is not the case.[7]
They reported that an increase in energy density from 2 J to 3.6 J at propellant area of 0.5 cm^2 results in a decrease in propellant charring or carbonization of the Teflon surface. However, their studies[7] have shown that decreasing propellant surface area to prevent propellant charring has a limit, after which no discernible difference is observed. For example a reduction in electrode width and therefore propellant surface area from 12 to 6 mm had little effect on charring at 2 J, but no charring was observed on increasing discharge energy from 2 to 2.3 J. Also increasing energy density results in the PPT operating at higher temperature thus increasing late time ablation which may be a factor that causes miniaturized PPTs to display reduced efficiencies compared to larger models.[7]
Due to the ambiguity surrounding the impact of electrode geometry on performance particularly for miniature PPTs, it is necessary to investigate in more depth the dependence of performance on geometry. It is expected that extreme miniaturization will even change the physics of the acceleration process, e.g. effects such as viscous boundary losses might become more important.[7]

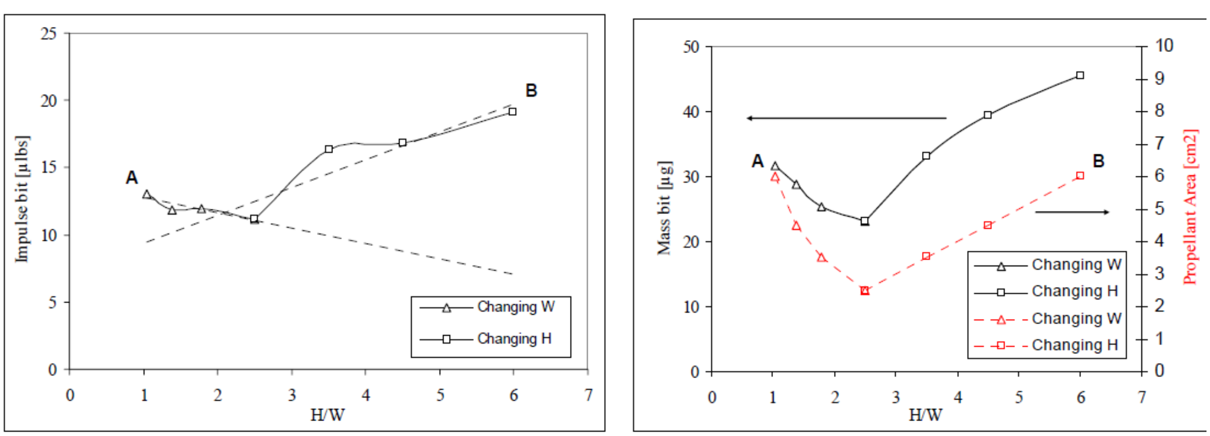

Figure 2. Performance change correlated with changes in electrode width or electrode gap at 3.7 J. [7]

2. Electrode Length

Electrode length is one of PPT geometrical factors for which there is still ambiguity about its effect on the thruster performance characteristics and further investigation is needed to clarify it. Guman and Peko [2] studied the effect of electrode length on PPT impulse bit and specific impulse. They tested thruster with electrode length lower than 0.5 inch up to 3 inches at two different discharge energies of 5 and 10 J and the results claimed that thruster with smaller electrode length produce more specific thrust (thrust/power) and yield a higher specific impulse.[2] Figures 3 and 4 show thruster specific thrust and specific impulse as a function of electrode length taken from Ref. 2.

On the contrary, Arrington et al.[9] at NASA Lewis Research Center conducted research on the same topic and reported different results. They studied thrusters with 2.54 and 3.81 cm electrode length at 43 J discharge energy with parallel electrodes and their results claimed that thruster with longer electrodes lead to more specific impulse, and more thruster efficiency but less impulse bit and less specific thrust (thrust/power).[9] The results taken from Ref. 9 contradict the results from Ref. 2 as they report different results for specific impulse when electrode length increases. The fact that the two studies were done at different discharge energies raises the question of a possible correlation between electrode length, discharge energy, and performance.

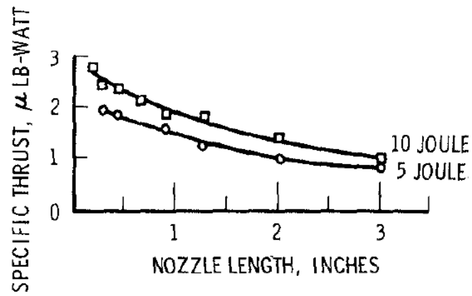

Figure 3. Specific thrust as a function of electrode length.[2]

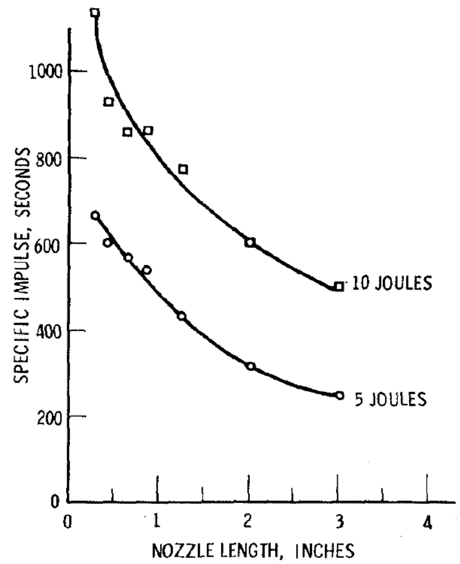

Figure 4. Specific impulse as a function of electrode length.[2]

Table 5 Performance characteristics as a function of electrode length.

Electrode Length (cm)	3.81	2.54
Fuel Face	Flat	Flat
Flare Angle, degrees	0	0
Capacitor Energy, Joules	43	43
Impulse bit (μN-s)	694	726
Specific Impulse (s)	1200	1121
Thrust/Power (μN-s/J)	16.1	16.9
Efficiency (%)	9.5	9

3. Flare Angle and Electrode Shape

The angle between electrodes (flare angle) is also another factor that can be used to optimize PPT performance. Palumbo and Guman[3] reported a series of thruster performance tests at high power 450 J discharge energy to assess the effect of the flare angle on thruster performance. In side-fed configuration, the electrode spacing (h) and propellant rod spacing (distance between propellant rods) were held constant at 7.62 cm, and 9.53 mm respectively, during these tests; the electrode length was 4.06 cm and the width 3.81 cm in all cases. In the breech-fed case, the propellant was a 6.35-mm thick slab of Teflon measuring 1.9 cm wide and 7.42 cm high. Results taken from Ref. 3 are presented graphically in Fig. 5. It was observed that a significant increase in performance level was realized for both geometries by increasing the electrode angle from zero to 20 degrees. In particular, the thrust/power ratio of the breech-fed geometry was increased from 20.4 to 21.1 mN/kW, while specific impulse also increased from 4730 to 5160 s. Increases in both of these parameters resulted

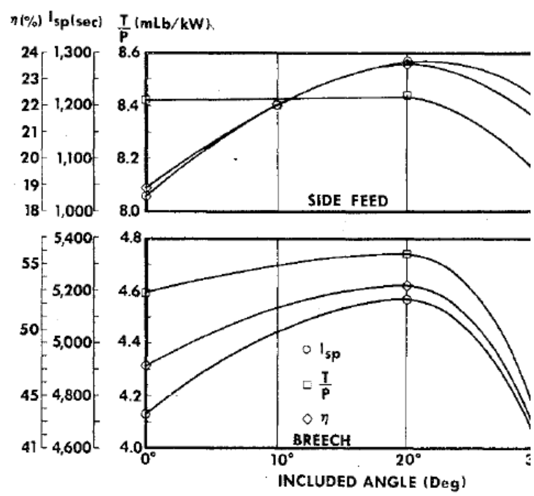

Figure 5. PPT performance as function of flare angle at an electrode spacing of 7.62 cm. [3]

in a 6.1% increase in efficiency (from 47.3 to 53.4%). A similar trend was reported for the side-fed geometry and although the thrust/power increment was within the range of their experimental accuracy, the specific impulse showed a 24.3% increase from 1030 to 1280 s and efficiency was, therefore, increased from 18.9 to 23.6%.[3]

Similarly, Arrington[9] studied the effect of flare angle on the performance of a thruster with 43 J discharge energy and 3.81 cm electrode length. Their results show that by increasing the flare angle from 0 to 20 degrees, impulse bit, specific impulse, thrust/power ratio, and efficiency increase from 694 to 794 µN-s, 1200 to 1228 s, 16.1 to 17.1 µN-s/J, and 9.5 to 10.3 % respectively.[9]

Further investigation studying the effects of flare angle on performance characteristics in more detail was carried out by Schönherr et al.[10] at IRS. They also studied the effects of electrode shape by comparing the results of rectangular and tongue shape electrodes. Their results[10] confirm the increment of impulse bit when flare angle increases from 0 to 20 degrees but declare a decrease when flare angle increases from 20 to 30 degrees. Figure 6 shows the result of that study. Furthermore, they studied the influence of flare angle on mean exhaust velocity (Fig. 7), thruster efficiency (Fig. 8), and thruster mass bit (Fig. 9). Based on the results taken from Ref. 10, tongue shape electrodes compared to rectangular shape electrodes give more impulse bit, more mean exhaust velocity, more efficiency, and less mass bit which means more specific impulse at the same test conditions.

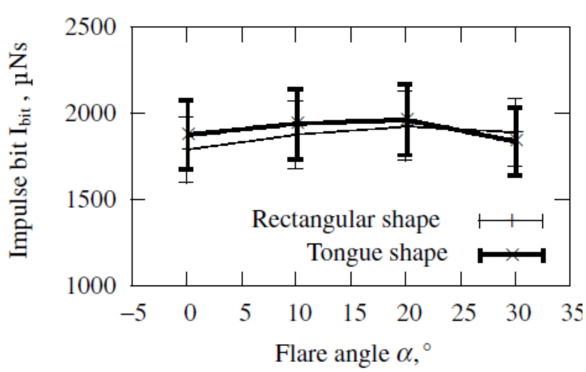

Figure 6. Impulse bit vs. flare angle for different electrode shapes.[10]

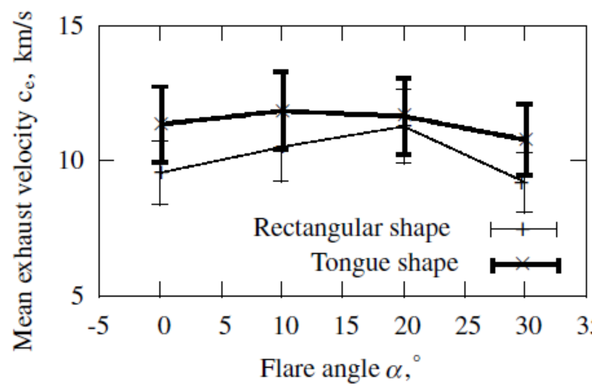

Figure 7. Mean exhaust velocity vs. flare angle for different electrode shapes.[10]

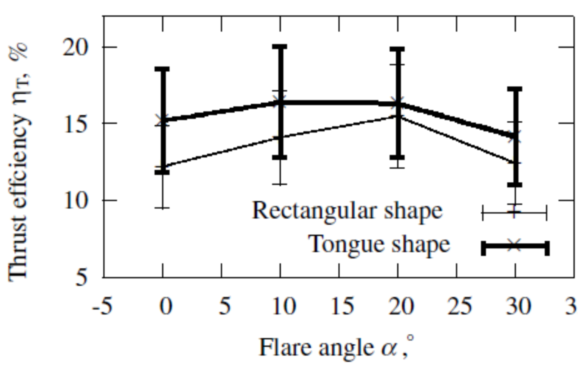

Figure 8. Thrust efficiency vs. flare angle for different electrode shapes.[10]

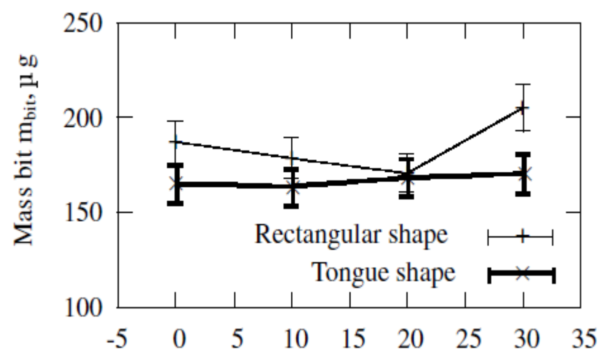

Figure 9. Mass bit vs. flare angle for different electrode shapes.[10]

4. Electrode Material

Three different materials have been suggested and investigated for utilization as electrode material, Copper, Brass, and Molybdenum but Copper has a good heritage as being used in several flight-PPTs. Kumagai et al. [11] at Tokyo Metropolitan Institute of Technology studied Molybdenum and Brass and compared their effect on performance (Table 6). The results show a better performance when

Table 6 Result of electrode material change.[11]

	Mo	Brass
Energy, J	3.6	3.6
I_{sp}, s	1129	1015
I_{bit}, µN-s	29.4	28
Mass shot, µg	2.66	2.44
Cathode erosion, µg	0.114	0.252
Anode erosion, µg	0.041	0.195
Thermal conductivity	139	106
Electrical resistivity	5.6e-8	6e-8

Molybdenum is used as the electrode material compared to the brass at the same test conditions.
Although there have been some research carried out testing Aluminum at IRS and Stainless Steel in Tokyo as electrode material but the results are not published yet.

D. Spark Distance from Propellant Face

Igniter plug spark distance from propellant face seems to be another parameter which can affect the thruster performance as the results of the study done by Vondra and Thomassen[12] at MIT Lincoln Laboratory proved the fact. Figure 10 taken from Ref. 12 shows that increasing the spark distance from propellant surface from 1/16 inch to 3/16 inch, increases the thruster specific impulse and efficiency but impulse bit does not change significantly and also mass shot reduces. On the other hand, increasing the distance from 3/16 inch to 7/16 inch has a quite different effect and decreases impulse bit, specific impulse, efficiency, and mass shot. It can be inferred that an optimum distance is achievable in each design.

E. Discharge Energy

One of the most influential factors which is essential in each PPT design is the required power. Required power is a function of discharge energy and working frequency. Thus, discharge energy is an important element in each design and the effect of which must be completely known. Furthermore, discharge energy is the best parameter to be changed and adjusted, when a multi-mode PPT with different levels of thrust is to be designed.

Numerous studies have been done to clarify the effect of discharge energy on PPT performance including Guman and Peko[2] at Fairchild Industries, Kamhawi et al.[13] at Ohio State University, Benson and Arrington[14] at GRC, Pottinger and Scharlemann[7] at Austrian Research Center, and Rezaeiha et al.[15] at Sharif University of Technology. All the studies unanimously report a quite linear relationship between discharge energy and impulse bit, and discharge energy and specific impulse. Although performance parameters presented in Ref. 7 and 15 were calculated from empirical relations and indirect measurement of thrust but the trend observed by them shows a reasonable compliance with the trend derived from direct measurement of thrust and performance parameters from Ref. 2, 13, and 14.

Table 7 Performance characteristics vs. discharge energy. [15]

Vo	E (J)	I_{bit} (μN-s)	I_{sp} (s)	M_{bit} (μg)	η	C_e (km/s)
750	9.84	476	200	242	5%	1.96
1000	17.5	663	366	184	7%	3.60
1250	27.3	943	525	183	9%	5.15
1500	39.3	1118	800	142	11%	7.87
1750	54	1323	1100	122	13%	10.84

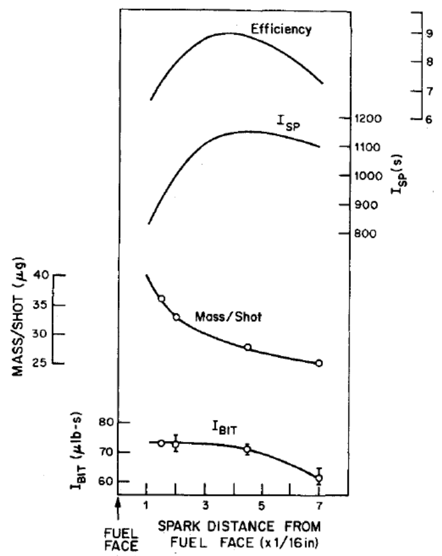

Figure 10. Performance characteristics as a function of spark distance from propellant face.[12]

F. Bank capacitance

Albeit already included in the discharge energy, the influence of the capacitance of the bank capacitors on the performance characteristics was studied in the past. This was done to clarify whether a better understanding of the oscillation behavior of the PPT can yield an increased performance.

Nawaz et al.[16] at IRS studied the effect on the thrust efficiency and the oscillation of the discharge voltage by both theory and experiment. Theory showed that the effect of the capacitance depends on the inductance of the circuit, but a general improvement for higher capacitance was found (also refer to Fig. 11). Experiment with a thruster at higher capacitance confirmed the improvement in performance.

The oscillation behavior was studied concurrently with regard to the discharge voltage. An increase in discharge period was found with a higher capacitance as well as a less oscillating behavior. This study was continued by Schönherr et al.[17] at the University of Tokyo where the oscillation behavior was studied not only for a variation of capacitance but with the discharge voltage alike. Additionally, the discharge current was studied as well. Again, an increase in capacitance yielded a higher damping of the oscillation depending on the voltage level applied. Regarding the discharge current, the peak current was found to be relatively smaller for a higher capacitance, i.e., increase of capacitance by factor 4 yielded an increase in peak current by 2.5. However, the achievable current action integral per capacitor was found to be significantly higher for the higher capacitance (see Fig. 12) implying a higher energy density in the discharge arc, and thus, a better performance of the thruster.

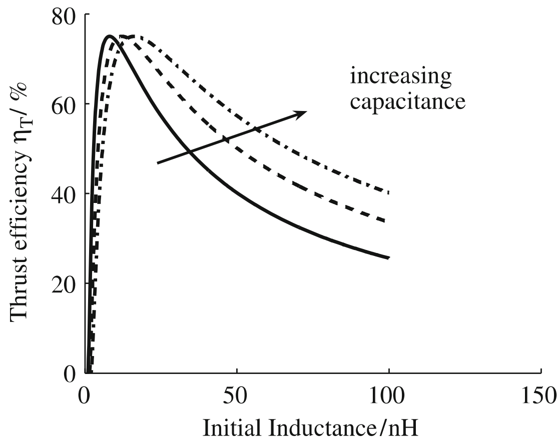

Figure 11. Thrust efficiency vs. initial inductance for a variation in capacitance. [16]

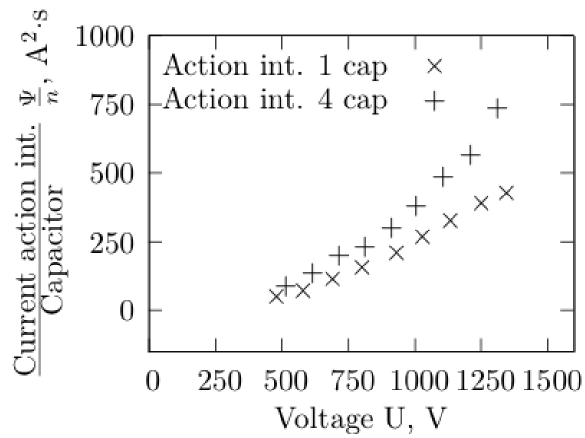

Figure 12. Normalized current action integrals for a variation in voltage and capacitance.[17]

F. Thruster working frequency

Antropov et al.[18] at RIAME tested PPT with different working frequencies and studied its effect on thruster efficiency (Fig. 13), total impulse (Fig. 14) and their study shows an optimum working frequency. Table 8 presents the data taken from Ref. 16 when the frequency varied from 3 Hz to 15 Hz.

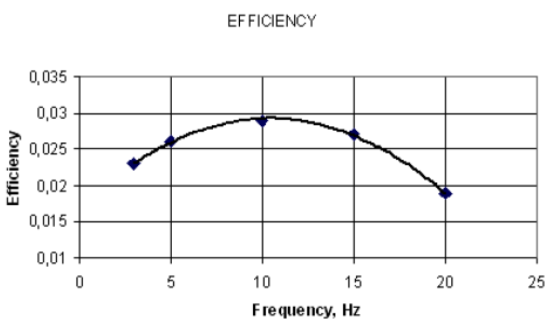

Figure 13. Thruster efficiency vs. working frequency.[18]

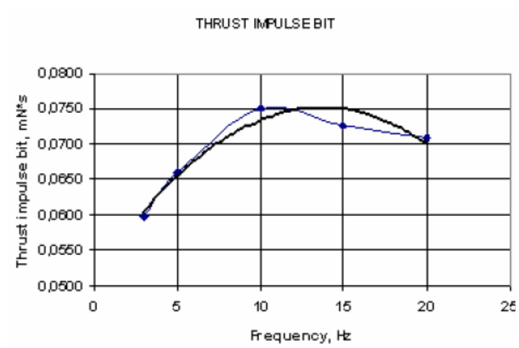

Figure 14. Total impulse bit vs. working frequency.[18]

Table 8 Micro APPT parameters for 3 – 15 Hz repetition frequency.[18]

Capacitance, µF	Voltage, V	Frequency, Hz	Consumption per pulse, g	Thrust impulse bit, mN*s	Energy, J	Power, W	Efficiency
4.5	1300	3	2.07E-05	0.0598	3.8025	11.4075	0.023
4.5	1300	5	2.17E-05	0.0660	3.8025	19.0125	0.026
4.5	1300	10	2.57E-05	0.0751	3.8025	38.025	0.029
4.5	1300	15	2.63E-05	0.0727	3.8025	57.0375	0.027

G. Hood Angle

Considering the PPT integration to the satellite, the contamination shield hood is necessary to prevent the PPT plume from spreading and contaminating on the satellite surface. However, the opening angle of the hood affects the PPT performance. Kumagai et al.[11] at Tokyo Metropolitan Institute of Technology studied this effect and reported that contamination distribution did not change with over about 40 degrees hood and that the narrower the opening angle of the hood became, less than about 40 degree, the narrower the contamination distribution was. Furthermore, in case of a too narrow opening angle, a reduction of impulse bit was reported. Hence, they evaluated the effect of the hood angle on the PPT performance with 0, 15, 30, 45, 60 degrees hoods.[11]

In their experiment, the hood angle was defined to be the half angle of the opening angle of hood as shown in Fig. 15. And in this experiment two different thruster heads were used, one with Molybdenum electrodes and the other with Brass electrodes. Figure 16 and 17 show impulse bit, and specific impulse of the operation with 0, 15, 30, 45, 60 degrees hoods and without hood. In these figures, 180 degrees points indicate the value of without hood operation. Also they stated that the mass shot was not significantly different with each angle hoods and without hood. On the other hand, as shown in Fig. 14, the impulse bit with each of the hoods indicates low values compared to the operation without hood. Furthermore, specific impulse and specific impulse with 15, 30, 45, and 60 degrees hood are quite close to each other. Zero degree operation, in particular, did in contrast and indicated the lowest value. A possible reason for the decrease observed in the thruster impulse bit with 0 degree hood is the momentum loss of plume by collision with the hood inner wall.[11] As in the other studies on PPT plume[19-21], it was reported that the spread angle of charged particles ejected from PPT is about 30 - 40 degree and it justifies the loss.

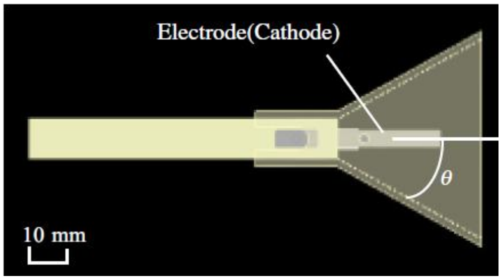

Figure 15. TMIT PPT with θ degree hood angle. [11]

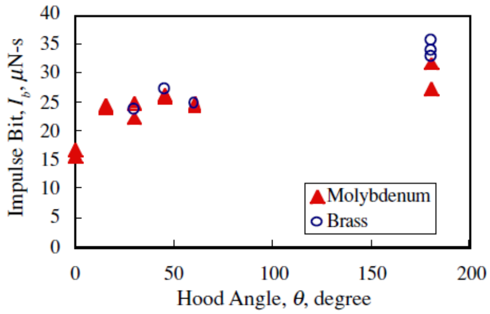

Figure 16. Impulse bit vs. hood angle for two different electrode materials.[11]

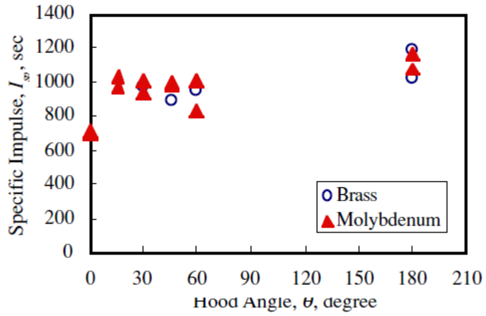

Figure 17. Specific impulse vs. hood angle for two different electrode materials.[11]

III. Conclusion

A thorough overview has been done to clarify the effects of different influential parameters on PPT performance based on the most significant studies ever done worldwide. The present paper reviewed the effects of the most important geometrical parameters like electrode dimensions/spacing/flare angle/shape, propellant face area, distance between plug arc and propellant face as well as other effective factors like propellant material/temperature, electrode material, and discharge energy on PPT performance. In addition, an analysis has been done on the results of each study to derive a point useful in PPT design process. The current study can be a major assistance in design and optimization process of ablative rectangular breech-fed and side-fed pulsed plasma thrusters.

Acknowledgments

The authors would like to express their special thanks to all the scientists and researchers worldwide, academic or non-academic, who have ever conducted research on PPTs, either mentioned on the references or not; as the present work could not be possible without their efforts throughout the years.

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