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An Overview of Activities in Liquid-fed PPT

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Abstract

Pulsed plasma thrusters (PPTs) are widely known for their simplicity, reliability, zero stand-by power, variable thrust level, and low power requirements. However, their low efficiency has been always considered as a major drawback. There have been many studies conducted so far to improve PPT performance to attain higher total efficiencies which include research on PPT geometrical parameters, capacitance, working frequency, propellant feeding method, discharge energy, etc. Additionally, several studies have been carried out to investigate the possibility of utilizing alternative propellants rather than the typical PTFE (Polytetrafluoroethylene). Some of the alternative propellants investigated include some other fluorocarbons, liquids, gases, and liquid-metals. The results have proposed that liquid propellants like water, cesium, lithium, and mercury can be promising. During the late 1960s and early 1970s, a pulsed plasma thruster (PPT) was developed by the Royal Aerospace Establishment (RAE) at Farnborough. A conventional rail gun concept using the same propellant as an ion thruster being developed simultaneously; this was mercury. However, liquid-fed PPTs were first extensively studied by The Ohio State University in late 90s when they numerically studied the use of water, Cs, and Li and compared their performance to PTFE (Teflon®) and also developed a PPT which was tested using water. The results showed the impressive improvement in thrust to power range. The research was continued by The University of Tokyo where they operated a water propellant PPT with impulse bits in the range from 22 to 82 μN-s with discharge energy of 3 to 13.5 J. The present paper intends to extensively review all the worldwide activities conducted so far, focused on the research and development of liquid-fed PPTs (LPPT[1]).

Introduction

Pulsed plasma thrusters (PPTs) are extensively recognized as one of the most promising propulsion systems to perform propulsive tasks on micro- and nano-satellites including CubeSats as they offer many advantages compared to other systems; simplicity, low size and low mass, low power requirements, zero stand-by power, high reliability, variable thrust level, discreet impulse bits compatible with digital logic, performance compatible with attitude control and stationkeeping requirements, operation at large variation in environmental temperature, and thrust vector control capability.[1)]

However, the PPT low efficiency has been always considered as a major drawback resulting in many experimental studies to improve PPT performance to attain higher total efficiencies. Basically, PPT performance is influenced by many parameters[2)] which have been the center of attention in past research. They include geometrical parameters, capacitance, working frequency, propellant feeding method, discharge energy, etc. and the result of the studies have been quite effective in making the PPT more efficient compared to earlier models but it still needs to be improved. Table 1 shows a comparison of performance of various PPTs with respect to their development year, taken from Ref. 1, 3, and 4. When comparing several flight-ready PPT models developed in different years, LES-6 (1968), LES-8/9 (1976), EO-1[5)] (2000), SIMP-LEX[4)] (2009), and ADD SIMP-LEX[4)] (2010); the enhancement of performance is quite plausible. Additionally, Nawaz et al.[6)] presents a high-efficiency PPT, a version of ADD SIMP-LEX, producing an impulse bit of 420 μN-s with an specific impulse of 2600 s using an energy of 17 J at a thrust efficiency of 31%.

Considering all the improvements and in spite of the many benefits of PPT, its efficiency compared to other types of electric propulsion systems is still low, but offers a very high specific impulse at lower energy levels, important for satellites with limited supply of energy and propellant. Figure 1 depicts a very good comparison of the nominal efficiencies of many types of electric propulsion systems which is a good aid to understand the current classification of electric propulsion systems in the light of thrust efficiency. It can be inferred that PPTs, along with steady-state MPD thrusters and arcjets yield the lowest efficiencies of all.

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[1] Nomenclature standard defined by the International PPT & iMPD Working Group.

Table 1 Comparison of PPTs performance with respect to their development year.[1,3,4]

Thruster	E (J)	I_{sp} (s)	I_{bit} (μN-s)	η (%)	Year
Zond-2	50	410	2000	8	1964
LES-6	1.85	300	26	2	1968
SMS	8.4	450	133	3.7	1974
LES 8/9	20	1000	297	7.4	1976
MIT-Lab	20	600	454	6.6	1976
Japan Lab	30.4	423	469	3.2	1979
TIP-II (NOVA)	20	850	375	7.6	1981
MDT-2A	4	280	60	2	1981
China Lab	23.9	990	448	9.3	1984
Millipound	750	1210	22,300	17	1995
Primex-NASA	43	1136	737	9.8	1995
MIPD-3	100	1130	2250	12	1996
Mighty-Sat II.1	40	1150	750	9.8	1999
EO-1	24.4	1150	316	7.6	2000
Dawgstar	12.5	500	70	1.5	2001
SIMP-LEX[4]	68	1800	900	12	2009
ADD SIMP-LEX[4]	68	2600	1375	26	2010
Sharif U of T-PPT-1[3]	27.3	525	943	9	2010
Sharif U of T-PPT-2[3]	39.3	800	1118	11	2010

Besides the aforementioned aspects previously investigated to optimize PPTs, utilization of alternative propellants can be also considered. Several studies have been carried out to investigate the possibility of utilizing alternative propellants rather than the typical PTFE (Polytetrafluoroethylene). Some of the alternative propellants investigated include some other fluorocarbons[8-10], composite propellants[11-12], powdered propellants[13], liquids[14], gases[15], and liquid-metals[16]. The results have proposed that liquid propellants like water, cesium, lithium, and mercury can be promising. During the late 1960s and early 1970s, a pulsed plasma thruster (PPT) was developed by the Royal Aerospace Establishment (RAE) at Farnborough.[17] A conventional rail gun concept using the same propellant (mercury) as an ion thruster was developed simultaneously. However, liquid-fed PPTs were first extensively studied by The Ohio State University in late 1990s[14] when they numerically studied the use of water, Cs, and Li and compared their performance to PTFE and also developed a PPT which was tested using water. The results showed the impressive improvement in thrust to power range. Similar research was conducted at The University of Tokyo[18] where they operated a water propellant PPT with impulse bits in the range from 22 to 82 μN-s with discharge energy of 3 to 13.5 J. The present paper intends to extensively review all the worldwide activities conducted so far, focused on the research and development of liquid-fed PPTs; and provide a database to assist any future research on the topic.

Early Research at Royal Aerospace Establishment, Farnborough, UK[17]

During the mid-1960s and in parallel with the initial development of two ion thrusters (T5 and T6 thrusters) by QinetiQ, the results of an investigation on the requirements for spacecraft propulsion led to the necessity for a low-thrust system for attitude control missions and pulsed plasma thruster was selected to be developed to take over the task.

Pulsed plasma thrusters were presumed to be simpler to construct and to operate than ion thrusters, requiring less complex power supplies and control circuitry, and were able to produce minute impulse bits with durations as short as 1 μs. Limitations were thought to include poor electrical and mass utilization efficiencies, but the former was not considered to be

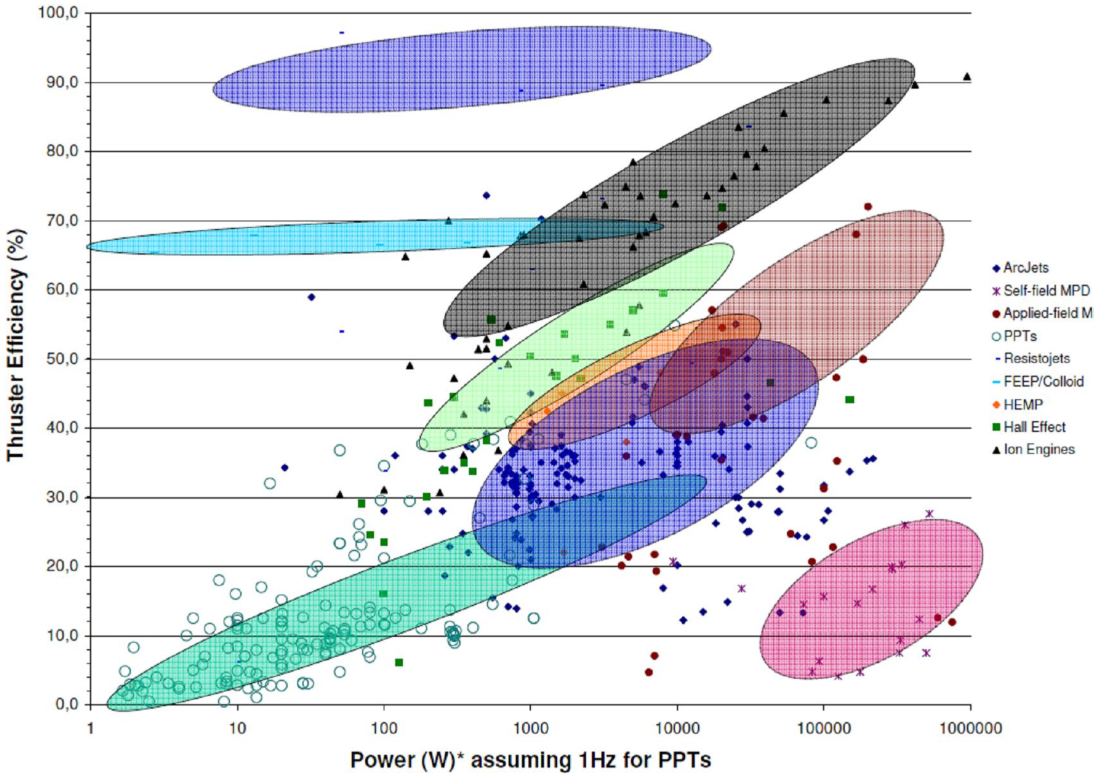

Fig. 1 Efficiency comparison among different EP technologies.[7]

serious in applications where large amounts of power were available, and the latter did not appear to cause an unacceptable mass increase for most missions of interest.[17)]

The PPT was aimed to develop 0.5 mN of thrust at an electrical efficiency of more than 10% and working frequency was expected to be determined by experiment. The total development process lasted four years in late 1960s and early 70s. A breech-fed concept was chosen for simplicity and also to avoid the current sheet instabilities often found in coaxial configuration.[17)] Additionally, the electrode configuration was flared and rectangular.

At the time, it was considered that there will be many advantages to employ the same propellant for PPT and ion thrusters, which was mercury. So that mercury was utilized mainly for the commonality of the programs, although high atomic weight and ease of storage was also favorable. Gaseous propellants which can be more precisely injected into the thruster were temporarily rejected as a result of the potential unreliability of fast valves and storage difficulties.

The program focused on several aspects listed below:

- Observation of the plasma acceleration process and grasping an understanding of the processes responsible
- Investigation of the discharge initiation mechanism
- Study of the plasma using a Calorimeter, Langmuir probes and image converter high-speed photography
- Thrust measurement using sensitive thrust balance and evaluation of electrical and mass utilization efficiencies

The PPT utilized two 0.5 cm x 10 cm electrodes made of stainless steel, mounted on a boron nitride breech and diverged by 15° to maximize the total inductance while keeping their separation small at the breech to help the discharge initiation. The electrodes were separated using a plate of insulating boron nitride on one side and glass on the other side to allow plasma photography. A schematic of the system can be seen in Fig. 2.

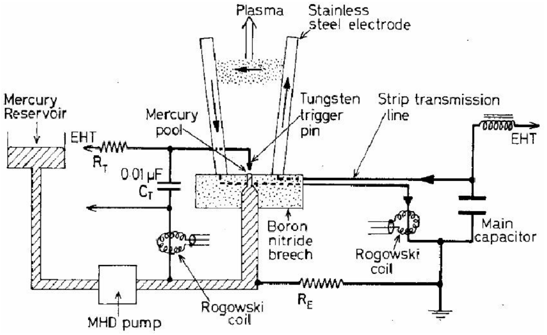

Fig. 2 Schematic of the thruster using mercury as propellant.[17)]

The propellant feeding was through a 1-mm-diameter hole by an MHD pump. Furthermore, a low inductance capacitor of 1.0 or 1.3 μF was used as the main capacitor. The Rogowski coil showed a 2.5 μs discharge pulse with a peak current of 560 A at 4 kV. Discharge initiation system used a pointed trigger pin placed about 1 mm above the propellant entrance which was connected to a 0.01-μF capacitor. The initiation process ionized about 0.3 μg of mercury at 2 kV at about 1 μs.

Although this discharge initiating system functioned satisfactorily, after long periods of operation reproducibility deteriorated. This problem was solved by the use of a two-stage process. In this system, the initiating discharge was itself initiated by another small arc between the mercury pool and a refractory semiconductor on applying a 400 V pulse to the latter. Figure 3 shows a schematic of the two stage system. This process, using silicon carbide rather than boron carbide, allowed 20 discharges per second to be maintained indefinitely; giving the system the possibility to work at 20 Hz.

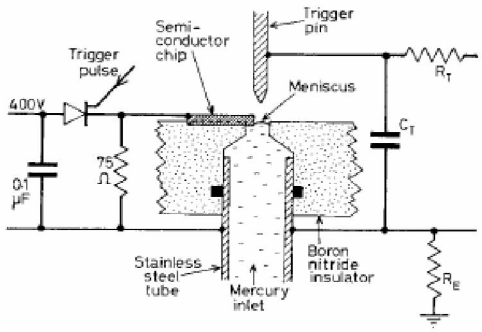

Fig. 3 Schematic of two-stage discharge initiation system.[17)]

While PPT was on test in vacuum chamber electron number density and electron temperature were measured using a double Langmuir probe and the plasma acceleration process was studied by image converter photography and magnetic probes, while the current was monitored using Rogowski coils. The results of the tests with a 1.3 μF capacitor charged with 2 kV shows that each pulse comprises of 3 discrete plasma sheets accelerating towards the muzzle of the thruster nozzle as the first front accelerates from 19 km/s at the breech to a maximum speed of 70 km/s and decelerates to 20 km/s at the time the second front has been formed. The following fronts also follow the same trend with lower maximum velocity. Interactions between the magnetic fields produced by current sheets through individual plasma fronts were thought to cause the variable velocities of each front.

In addition, Calorimeter was used to indicate the energy content of the thruster exhaust to compare the performance of different capacitors and the result revealed that the capacitor with the lowest inductance and resistance gave the greatest energy content, although low internal resistance appeared to be the a more important factor.

Finally, during the performance tests by thrust balance, the thruster produced an impulse, giving an instantaneous thrust of perhaps 50 N for a time of less than 1 µs yielding an impulse bit of 50 µN-s at 4.5 kV. Therefore, to achieve the design goals, the PPT was operated at 10 Hz.

Significantly, despite the optical evidence, a Langmuir double probe showed that the exhaust, some distance from the nozzle, consisted of a single high velocity plasma. Values of its velocity were combined with the impulse measurements to give the effective mass. This was comparable with the mass of mercury vapor produced by the trigger discharge, but far less than the total mass ablated from the mercury meniscus during the main discharge. Clearly, the latter was not appreciably ionized or accelerated, and contributed little to the thrust, causing the mass utilization efficiency to be very low, at 0.2 to 0.5%. The electrical efficiency was much greater, being 3% at 2 kV and 25% at 4.5 kV.

It was thus concluded that the thruster efficiently accelerated a large proportion of the mass injected by the trigger discharge to high velocity, but the very much greater quantity of propellant introduced by the main discharge was wasted. It is possible that this additional mass might be largely eliminated by using a rectangular pulse of current with a duration equal to the acceleration time of the first plasma, thus eliminating the subsequent plasmas and much of the sputtering of the mercury meniscus.17)

Research at The Ohio State University, USA19-24)

As a PhD research14,19-24) at the Ohio State University an investigation on liquid-fed PPTs initiated in 1999 and ended in 2003 by Carsten A. Scharlemann. The result of the research showed some performance improvements of liquid propellant PPTs compared to the typical PTFE PPTs. However, the complexity of feeding system of liquid-fed PPTs compared to the simplicity of solid PTFE propellant PPTs, and the possibility of leakage are still considered as major disadvantages of liquid PPTs.

The research was motivated by prediction of analytic models of the possibility of extending the range of performance parameters of PPTs by using alternative propellants rather than PTFE. Therefore, analytical and numerical calculations (MACH2) were initiated to investigate the use of alternative propellants for PPT and the results indicated significant improvements in specific impulse and thrust-to-power ratios when alternative propellants such as lithium or water were utilized. Figure 4 depicts the variation of thrust-to-power ration versus specific impulse for different propellant like water, lithium, and cesium based on the numerical calculation by MACH2.

The numerical results initiated the experiments to investigate the changes in physical phenomena and thruster performance and water was the propellant of choice for the experimental work.

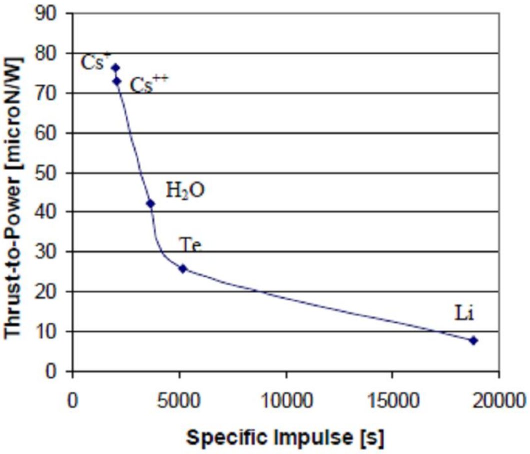

Fig. 4 Variation of thrust-to-power ratio vs. specific impulse for various propellants based on numerical calculations.14)

Thus, a unique hybrid PPT capable of utilizing PTFE and water without major changes in thruster geometry or circuitry was designed and developed which had a feed system and a supply of water. The electrodes are 2.54 cm long, 2.54 cm wide and separated by a 2.54 cm gap and the main capacitor is a 30 µF while the thruster was operated at 10, 20, and 30 J and 1 Hz. Figure 5 shows a picture of the thruster. The feed system employed a Passive Flow Control (PFC) concept based on the diffusion of the water propellant through a porous ceramic inlay. Synchronization issues between triggering the main discharge and supplying the propellant were avoided by supplying the water into the vicinity of the spark plug, from where it was delivered into the acceleration channel upon triggering the spark plug.19)

The thruster operation and performance using water and PTFE was studied using various diagnostic methods, including current and voltage measurements, Langmuir probes, and magnetic field probes and the results were compared to identify the influence of utilizing water as propellant for a PPT.

Additionally, a unique method was developed and used to calculate the impulse bit of the PPT by measuring the impact pressure in the plume and its accuracy was validated by direct comparison with impulse bits measured on a thrust stand at the NASA Glenn Research Center. 19)

To prove the electromagnetic nature of the water-fed PPT, magnetic field measurements and analytics were done. Also, the plasma exhaust velocity using Time-of-Flight measurements (by means of Langmuir probes and pressure probes) were evaluated to be a factor of 1.5 to 2 higher than that in the PTFE case, although the discharge currents in the water case are around 40% lower. Figure 6 displays discharge current and capacitor voltage for water and PTFE.

Table 2 Thruster performance for the both PPTs.21)

Discharge Energy (J)	Impulse bit, GRC (μN-s)		Impulse bit, pressure probe (μN-s)		Mass bit (μg/discharge)		Specific impulse (s)		Efficiency (%)	
	PTFE	Water	PTFE	Water	PTFE	Water	PTFE	Water	PTFE	Water
10	122	-	124	47	11.9	~1.1	1060	4355	6.5	10
20	273	-	281	90	27.5	~1.1	1040	8340	7.2	18
30	440	-	440	128	35.5	~1.1	1270	11860	9.1	24.8

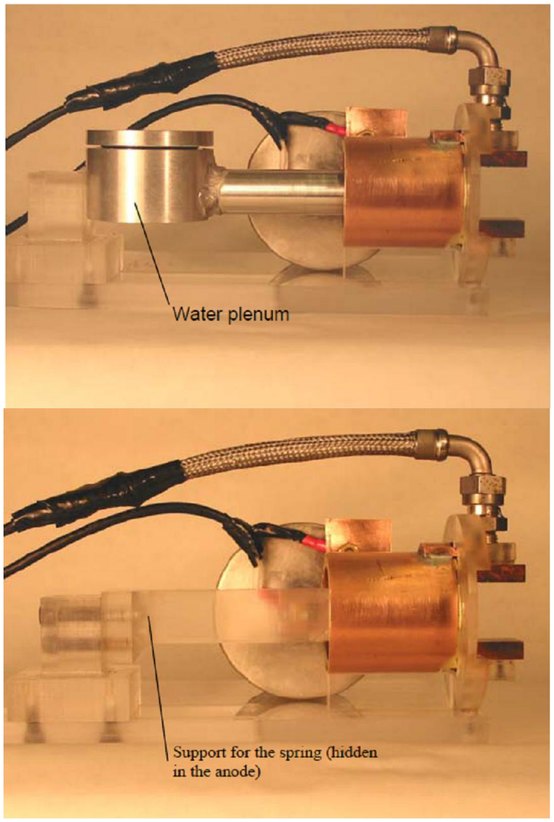

Fig. 5 The photograph of the liquid-fed PPT (above) and PTFE PPT (below) developed by The Ohio State University.14)

The lower discharge current was a result of 3-4 times lower conductivity and higher resistance of water plasma compared to PTFE plasma. Despite the lower discharge currents, higher exhaust velocities were confirmed using all the employed diagnostic methods in comparison with PTFE, and that was interpreted to be a result of a more efficient deposition of energy into kinetic energy and the apparent prevention of late time ablation which led to higher performance of water-fed thruster compared to a typical PTFE-PPT. The water thruster required only 5% of the mass bit of a PTFE thruster to produce 30% impulse bit of that at 30J, resulting in greatly increased propellant efficiencies. It was also mentioned that a specific impulse for the water thruster of up to 8000 s and efficiencies of up to 16% were evaluated.19) Table 2 shows the performance of the PPT for both water and PTFE and for pressure probe measurements and direct measurements at NASA GRC.

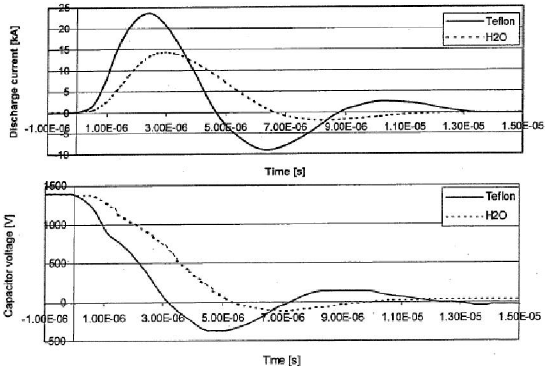

Fig. 6 Discharge current curve (above) and capacitor voltage curve (below) for water-fed and PTFE PPT.20)

Research at The University of Tokyo, Japan25-34)

A liquid-fed pulsed plasma thruster was designed and developed to compensate for the low efficiency of the more popular PTFE PPT in 2002.25) It was also proposed that the liquid-fed PPT might be able to wipe several other problems of ablative PPTs away; some problems like contamination, low thrust performance, late-ablation and low speed vapor after the main discharge, emission of large particulates, and non-uniformity in propellant consumption and current density and PTFE surface temperature.28-29) The PPT25) utilized an injector to provide methanol propellant ranging from 3.9 to 38 μg per shot to the thrust chamber at discharge energies of 3.4 to 13.5 J for main discharge, while the injector consumed 0.1-0.2 J of power (comparable to the energy of a PPT igniter plug). The spontaneous main discharge was initiated by feeding liquid propellant into the coaxial inter-electrode space by the intermittent injector at a combination of mass shot and the capacitor stored energy. Two mica-paper capacitors with capacitance of 3 μF were connected in parallel and charged with a 3 kV power supply to provide the PPT with the required energy for the main discharge.

Impulse bit measurements were performed on a torsional-type thrust stand designed to measure low impulse bits ranging from 10 to 1000 μN-s with high precision.26) The measurements give an impulse bit of 57 μN-s at a specific impulse of 1500 s, discharge energy of 13.5 J, mass shot of 3.8 μg, and thrust efficiency of 3.1%. However, the higher efficiency was proposed to be attainable at lower mass shots. In addition, the observed impedance mismatch between the power-source and plasma was predicted to be a reason for low efficiency, which could be improved by impedance matching.[25)]

The research was continued while the propellant changed to water and two new PPTs, one with coaxial electrodes and one with parallel ones were designed and it led to improvements in thruster performance. Figure 7 shows a schematic of both PPTs.[27)] The parallel electrodes were 50 x 10 x 5 mm^3 copper bars with 30-mm gap.

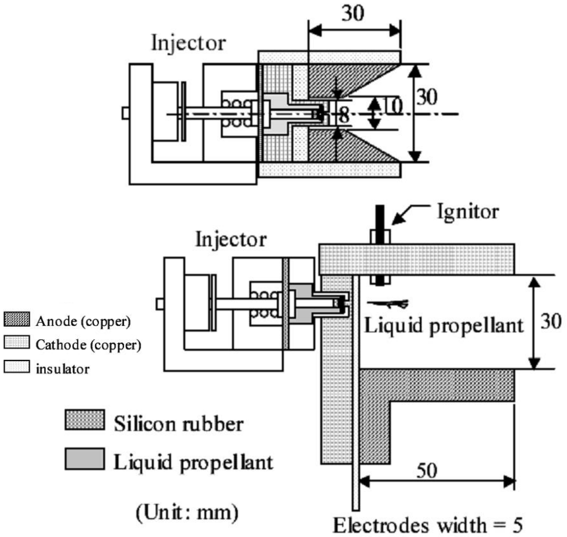

Fig. 7 Schematic of liquid-fed PPTs designed by the University of Tokyo, coaxial plates (above) and parallel plates with igniter plug (below).[27)]

The PPT utilized micro-machined liquid injectors of the 10 µg order to feed the water into the thruster chamber with high probability of spontaneous discharge initiation within the working discharge energies. Although igniter plug was used on parallel-plate PPT to increase the range of operation. Impulse bit measurements were accomplished using a thrust stand with the resolution of 1 µN-s and the PPT was successfully operated with high reproducibility. The impulse bits varied from 22 to 82 µN-s in proportion to the capacitor stored energy of 3 to 13.5 J. The PPT performance was improved with impulse bit of 89µN-s at a specific impulse of 3400 s, mass shot of 2.7 µg, discharge energy of 13.5 J, and thrust efficiency of 11%. Also, the standard deviation of the shot to shot variation was 4.5 µN-s.[27)]

Further efforts resulted in better performance; specific impulse of 4300 s, thrust efficiency of 13%, the mass-shot of 2.7 µg, and impulse bit of around 120 µN-s at 20 J energy.[28)] The research to improve the performance was accompanied by the research to clear the acceleration process and electromagnetic mechanism of liquid-fed PPT using LCR circuit analysis and ultra-high speed photography. It was observed that in PTFE PPT electrothermally-accelerated plasma particle moving slowly cause the lower specific impulse when such an event was not reported for liquid-fed PPTs. According to the LCR circuit analysis results, 60% of the total energy was consumed by the internal resistance of the main capacitor and 14% was used to accelerate the plasma electromagnetically in liquid-fed PPTs.[29)]

Up to this stage, the plume of the liquid-fed PPTs using water (or alcohol) as propellant was clean and this abolished the contamination of ablative PPTs. Furthermore, use of injector facilitated the throttleability of PPT and there was no further concern about the non-uniform propellant consumption. Although liquid propellant utilization issues, including feed system, fine synchronization between discharge initiation and feeding, and leakage probability were still of concern when liquid-fed PPTs were compared with PTFE PPTs.

The research to increase the thrust to power ratio of a liquid propellant pulsed plasma thruster was continued at The University of Tokyo and utilized two other ways for performance optimization and seeding additives into water propellant and enhancement of liquid vaporization by a micro-heater were investigated. The experiments show that thrust to power ratio of PPT is dependent on the total resistance of the discharge circuit. Therefore, the two methods were intended to increase the electrical conductivity of plasma. Table 3 indicates the typical resistance for LP-PPT and PTFE PPT at the energy of 10 J.[31-32)]

Table 3 Typical resistance of a LP-PPT and PTFE PPT at the energy of 10 J.[31)]

	LP-PPT	PTFE PPT
Thrust to power ratio	5.6 µN-s/J	8.4 µN-s/J
R_{total}	64±2 mΩ	48±1 mΩ
$R_{circuit}$	17±3 mΩ	17±3 mΩ
$R_{plasma} + R_{EM}$	47±5 mΩ	31±4 mΩ

To elaborate the methods to decrease the plasma resistance, it is preferred that they are explained separately.

At first, seeding in water propellant is reviewed. A method to increase the plasma electrical conductivity and decrease the plasma resistance, by increasing fractional ionization, is seeding. Injecting additives (which ionize at relatively lower temperatures than main species) into the plasma, supplies electrons which are needed for the ionization of main species. Therefore, sodium and ammonia were proposed as additives. The requirement for a good seeding material is low ionization potential and Sodium satisfies the condition but injecting a gas into water had difficulties so that sodium chloride was selected for the ease of use compared to sodium in gas state. Table 4 compares the ionization potential of water, sodium, and ammonia and the seed concentration to water by mole percent.

The results showed that seeding water with sodium chloride can increase the impulse bit from 60 to 66 µN-s at the energy of 11.5 J, which is a 10%

increment compared to pure water. The average increment over the measured energy range was 5.5% due to an average decrement of 5.8% in total resistance. However the total resistance was still higher than a PTFE PPT, probably because of lower total number density, rather than the fractional ionization.

On the other hand, injection of ammonia showed higher resistance even compared to pure water and decreased the thrust to power ratio. From the weaker emission lines, it was proposed that the plasma density became lower. Some energy might be excessively consumed for the dissociation of ammonia molecule. Figure 8 shows a comparison of thrust to power ratio for the aforementioned solutions while Fig. 9 shows akin resistance.[31-32]

Table 4 Properties of H2O, Na, and NH3.[31]

	Ionization potential	Seeding concentration
H_2O	12.7 eV (H_2O^+)	-
Na	5.1 eV (Na^+)	1.9%
NH_3	5.9 eV (NH_3^+)	5.5%

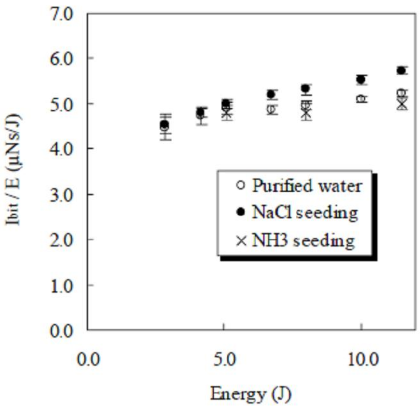

Fig. 8 Effect of seeding in thrust to power ratio.[31]

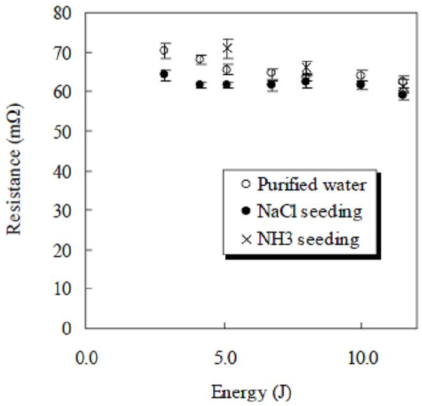

Fig. 9 Effect of seeding in total resistance of LP-PPT.[31]

Second method to improve the LPPT performance is increasing the vaporization using the micro-heater assembly. Two designs were used in the experiment; one with a single capacitor connected to electrodes and without any igniter plug, second a thruster utilizing two capacitors for the ignition and acceleration, which was double discharge type. Figure 10 shows a schematic of the systems.

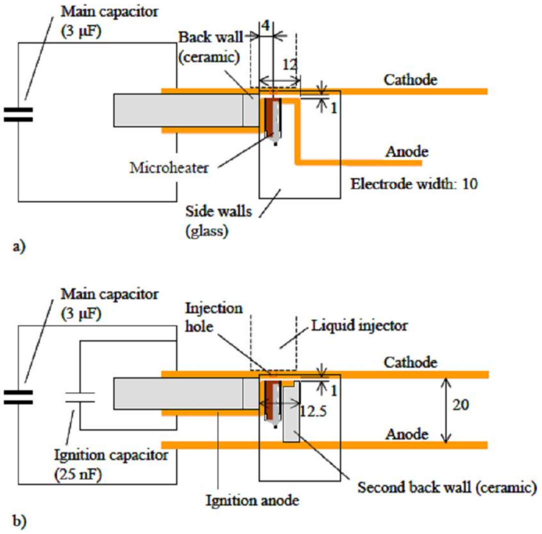

Fig. 10 LP-PPT using micro-heater evaporation, a) single discharge and b) double discharge.[31]

The single discharge LPPT using the micro-heater assembly were successfully operated spontaneously at the mass shot between 6-12 μg while keeping the heater temperature at 100ºC although when the mass shot was decreases below 6μg, spontaneous operation without use of igniter plug was in trouble. The PPT showed poor thrust to power ratio, below 2 μN-s/J, which was less than half of the previous LPPT studied. On the other hand, double discharge LPPT showed higher thrust-to-power ratio than the previously studied LPPT without heating. The thrust to power ratio increased with the energy and saturated around 10 J, where it reached up to 8 μN-s/J this is over 30% increment compared to previous studies without utilization of a heater. The specific impulse of 1550 s and the trust performance of 6.0% were attained at 10 J. From the results it was proposed that the higher thrust to power ratio was caused by the reduction in plasma resistance which itself is caused by the increment of the inter-electrode pressure as a result of the higher temperature (heating).[31]

Finally, the research on liquid-fed PPTs at The University of Tokyo focused the research on the comparison of plasma acceleration process and behavior of ablative PPTs and liquid propellant PPTs. The result of this stage were obtained using ultra-high speed photography (5 Mfps), emission spectroscopy, and magnetic field measurements for both ablative PPT and liquid propellant PPT and the results proved that utilization of liquid propellant instead of solid propellant yields higher specific impulse, higher exhaust velocity, and higher mass utilization efficiency; but lower impulse bit. The lower specific impulse of ablative PPT was believed to be a result of high-density low-speed neutral particles remained near the propellant surface after the main electromagnetic discharge. Figure 11 and 12 show a comparison of performance of APPT and LP-PPT and Fig. 13 compares the discharge currents at 10 J.

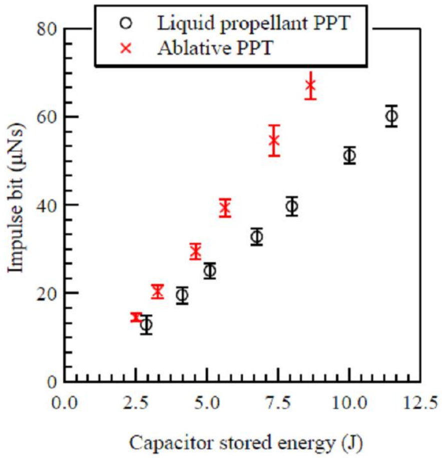

Fig. 11 Comparison of impulse bit for LP-PPT and PTFE PPT in a range of energy. 33)

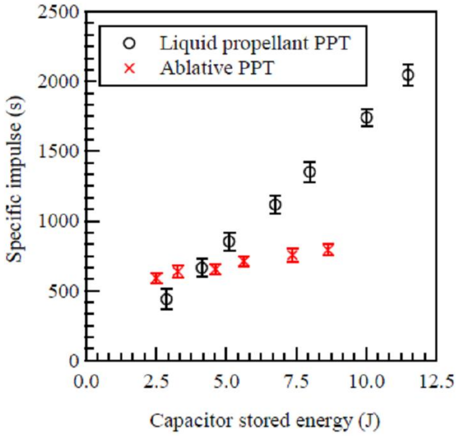

Fig. 12 Comparison of specific impulse for LP-PPT and PTFE PPT in a range of energy. 33)

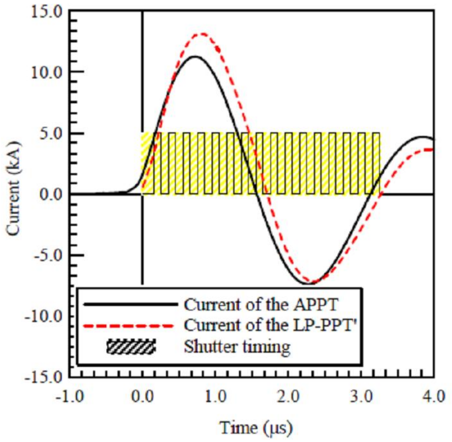

Fig. 13 Discharge current of LP-PPT and APPT.33)

Research at The John Hopkins University, USA35)

Light weight, low power miniaturized PPTs have been developed by the researchers at the John Hopkins University, Applied Physics Laboratory (JHU/APL). Two versions have been developed yet, PTFE μPPT and liquid-fed μPPT. It is mentioned that the latter could employ a wide variety of liquid propellants.

The small electrode gaps in this device permit operation at relatively low voltages. This significantly reduces the size and weight of associated power processing electronics and wiring. In fact, researchers at JHU/APL have developed miniature circuits to drive these thrusters from a low-voltage power source. Ultimately, the thruster fabrication process permits the integration of this circuitry directly onto the propulsive structure itself. Figure 14 illustrates the liquid-fed μPPT and Fig. 15 shows the prototype μPPT power processing circuit.

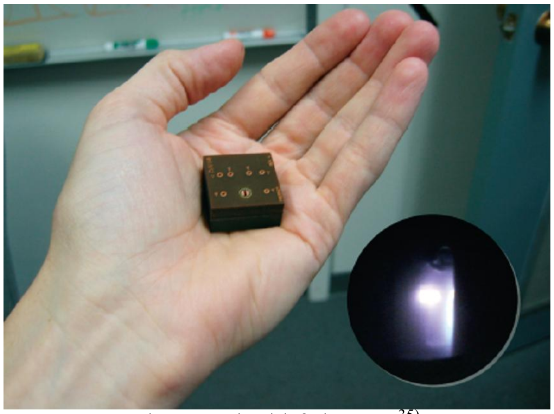

Fig. 14 Liquid-fed μPPT.35)

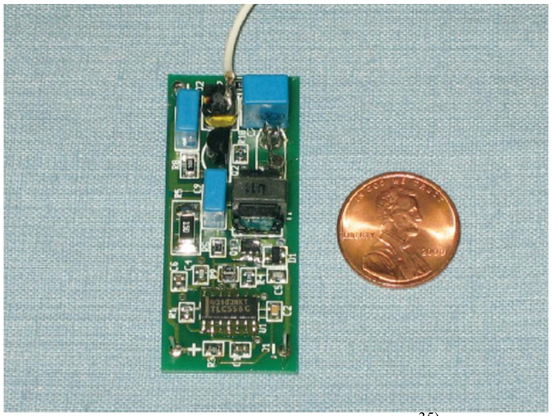

Fig. 15 Prototype μPPT PPU.35)

Cooperation between IRS and DLR, Germany36)

In a collaboration work between Institute of Structures and Design at German Aerospace Center (DLR) and Institute of Space Systems (IRS) at the University of Stuttgart, a liquid-fed PPT was developed and utilized to examine a permeable flow element for PPT water propellant feeding. It was found that the propellant transport was both driven by pressure gradients within the structure and evaporation into the discharge region. For functional testing, a mass flow rate of 340 µg/s was chosen and at an ambient pressure of 5 Pa, the thruster was successfully fired with water propellant and no random ignition was detected at capacitor voltage below 800 V. The ambient pressure for PTFE was 0.02 Pa. Photography, spectroscopy, and voltage monitoring were employed to observe the ignition behavior. The experiments were conducted in the test-stand shown in Fig. 16. The emission spectrum of the discharge clearly shows that the observed plasma consists of water (Fig. 17). Finally, the system was compared to a PTFE propellant system by spectrometric and photographic analysis of the plasma. However, visual comparison of the electrodes after a certain number of pulses indicates less erosion of the electrodes for water propellant PPT than with PTFE propellant. In the PTFE plasma, copper was found in the spectrum, indicating erosion of the electrodes. Moreover, PTFE additionally contaminated the electrodes with carbon and fluoride residues whereas no visual deposition of contaminants from operation with water for identical test conditions in terms of energy was observed.[36)]

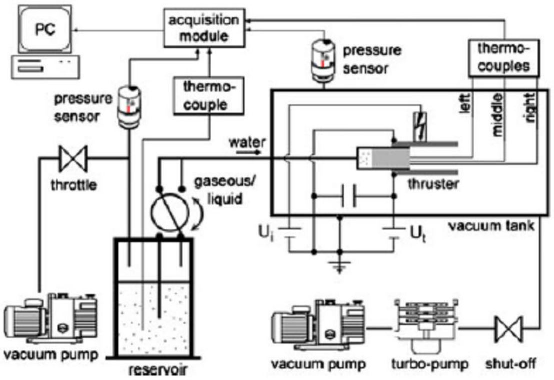

Fig. 16 Test setup for investigation of PPT operation and flow control.[36)]

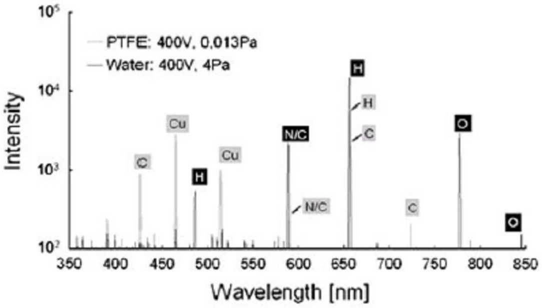

Fig. 17 Spectra of PTFE and water discharges.[36)]

Research at Kyushu Institute of Technology, Japan[37-38)]

As a result of a research at Kyushu Institute of Technology, a liquid-fed coaxial PPT was developed utilizing dimethyl ether (DME) as propellant. The reason behind choosing DME instead of water or ethanol was that water requires temperature management for propellant storage owing to relatively high freezing point, Even if ethanol, which has sufficiently low freezing point, was used as propellant, pressurant was necessary because the vapor pressures were deficient for self-pressurization. They proposed to use DME as PPT propellant, which has a freezing point of 131 K at 1 atm and a vapor pressure of 6 atm at 298 K, is storable in tanks as a liquid and requires no feeding pressurant. [37)]

They investigated the dependency of the thruster performance on discharge energy and propellant entrance cavity diameter. The following is a summary of the study:[37-38)]

- DME-PPT successfully fired without any random firing for cavity diameter 3-5 mm at 1-13 J.
- DME-PPT successfully operated for cavity diameter 2 mm at 2-13 J but the ignition probability decreased to 10% at 1 J.
- Impulse bit and specific impulse increased from 20 µN-s and 70 s to 130 µN-s, and 430 s respectively as energy increased from 1 to 13 J. Maximum thrust efficiency of 2% was achieved for DME-PPT.
- Maximum inductance and electrical resistance was experienced for cavity diameter of 2 mm.

However, it was proposed that thrust efficiency and specific impulse could be augmented by fine adjusting the mass shot. Figure 18 and 19 depicts the DME-PPT tests pan, and schematic respectively.

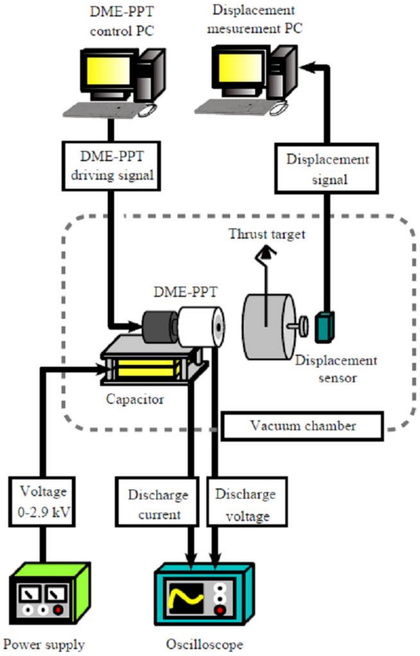

Fig. 18 DME-PPT test plan.[37)]

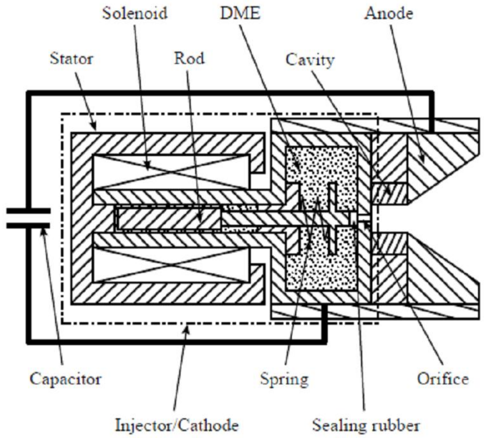

Fig. 19 Schematic of DME-PPT.[37)]

Conclusion

To improve PPT performance, liquid propellants have been investigated in several research projects which are reviewed here. The early research by Royal Aerospace Establishment at Farnborough, UK between late 1960s and early 70s, utilized mercury as PPT propellant and operated at 10Hz producing 0.5 mN of thrust at 4.5 kV using a 1.33 µF capacitor. The PPT attained mass utilization efficiency and electrical efficiency of 0.2-0.5% and 3-25% at 2-4.5 kV, respectively. In late 90s, a PhD research was initiated at the Ohio State University focusing on investigation of utilization of water as PPT propellant, its electromagnetic plasma acceleration process, and possible improvements in performance. Meanwhile, the results for water were compared to PTFE and thrust efficiency and specific impulse increased from 9.1% and 1270 s for PTFE to 24.8% and 11860 s for water at 30 J, when impulse bit reduced from 440 µN-s to 128 µN-s. Lower discharge currents were reported in case of water as a result of 3-4 times higher plasma resistance and higher exhaust velocities were believed to be a result of more efficient deposition of energy into kinetic energy and prevention of late-ablation. In early 2000s, a similar research commenced at The University of Tokyo, which resulted in development of several liquid-fed PPT models focusing mainly on spontaneous discharge PPTs. The early model used methanol but then water was chosen as propellant of choice for later models and thrust efficiency, impulse bit, and specific was improved from 3.1%, 57 µN-s, and 1500 s for the early model to 11%, 89 µN-s, and 3400 s at 13.5 J, respectively. Furthermore, two other methods for further improvement of performance were proposed, namely seeding the water propellant with sodium chloride and heating the propellant to dwindle the plasma resistivity and the methods were effective in increasing thrust-to-power ratio and impulse bit. The research also led to a complete understanding of the electromagnetic mechanism using ultra-high speed photography. A more recent research at the John Hopkins University in 2007 resulted in development of a miniature liquid-fed µPPT capable of utilizing many liquid propellants. Moreover, the results of a collaboration work between IRS and DLR indicated that electrodes were less eroded utilizing water as propellant instead of PTFE. In another research in Japan, DME was also proposed instead of water. However, it showed poor performance compared to water. After all, the results of the research on liquid-fed PPTs using water as propellant showed that it can yield to a better performance compared to typical PTFE PPT while it is less contaminative and more throttleable and less suffers from non-uniform propellant consumption, late-ablation, and electrode erosion. However, the perplexing feeding mechanism and concerns of utilization of liquid propellants compared to solid PTFE are still considered as disadvantages.

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