Use of Liquid Propellants in Pulsed Plasma Thrusters for Small Satellites

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Abstract: There is increasing interest in small satellites weighing in the range of 100 kg or less. In particular, satellites weighing 1 – 10 kg currently lack options for a suitable propulsion system for performing large-velocity-change (ΔV) maneuvers. Pulsed plasma thrusters are a simple form of electric propulsion that have been operated in orbit many times since the beginning of space exploration. Due to their inherently simple design, they are very attractive for use in small satellites. However, issues such as charring of the solid propellant and late-time ablation can contribute to lowering of the overall thruster lifetime and the propellant utilization efficiency. The use of liquid propellants in pulsed plasma thrusters can potentially resolve some of these problems. We are currently investigating two very different approaches to the implementation of liquid delivery in pulsed plasma thrusters: passive ablative liquid-feeding and active electrospray-assisted droplet delivery. The former uses a non-volatile liquid propellant that is passively delivered using capillary forces, while the latter employs the electrospray process with a volatile liquid propellant to deliver very small liquid droplets to the thruster. Some preliminary data is presented here along with recommendations for future designs. The two different approaches have the potential to increase the efficiency and versatility of liquid-fed pulsed plasma thrusters.

I. Introduction

WHILE the first artificial satellite, Sputnik, weighed only 83.6 kg, along with an increase in capabilities, the average size and weight of satellites have also increased over time. For example, a modern Boeing-built NAVSTAR Block IIF GPS satellite weighs 1,630 kg and a digital broadcast satellite, DIRECTV-14, weighs 6,300 kg. However, with the miniaturization of electronics, small satellites are currently being aggressively pursued as organizations and academic institutions aim to obtain space capabilities and perform space-based research. In contrast to modern commercial satellites, these small satellites weigh around 100 kg, and can even be lower than 10 kg.

In the next several years, SpaceX, known for their recent developments of a reusable booster and a crew vehicle, plans to launch several thousand satellites, weighing around 100 kg each, in order to provide internet access to remote areas. Another company, OneWeb, has funding from the Virgin Group and Qualcomm to build and launch a similar constellation of small satellites (around 650 in number) weighing about 125 kg each. Their intended use is also to provide broadband internet access to customers.

In addition to this, the CubeSat architecture, which usually weighs at most several kilograms per satellite, has been experiencing rapid growth in utilization. The NASA CubeSat Launch Initiative has been selecting CubeSat

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projects for launch either from the International Space Station, or as a secondary payload aboard another space launch.[1] For example, two CubeSats are scheduled to be launched with the Mars InSight lander in March 2016. To date, satellite projects from 29 American states have been selected for launch opportunities. The initiative is intended to promote the development of a spacecraft nation and develop innovative technology partnerships between NASA, the U.S. industry, and educational institutions. Furthermore, in May 2015, NASA released a pre-solicitation notice for proposals for the development of dedicated launch vehicles for small satellites (solicitation number NNK15542801R), where a launch provider is to send a total weight of 60 kg of small satellites either in a single launch or in two 30 kg payloads.

Compared with options available for larger satellites weighing several hundred kg and greater, there is a lack of suitable propulsion systems available for small satellites, especially for those in the 1 to 10 kg range. Without this, the satellites have absolutely no capability of changing their orbits once released, and will take up orbital space until orbital decay causes them to re-enter the atmosphere. If released at or below the approximate altitude of the International Space Station (~400 km), the typical orbital lifetime will be several months, limiting the buildup of orbital debris. However, at altitudes of just 500 km and greater, the orbital lifetimes begin to be measured in years, decades, and even centuries.[2]

It is inevitable that small satellites will eventually dominate greater altitudes. For example, the proposed OneWeb satellite constellation is planned to be located at orbital altitudes of 800 km and 950 km. Similarly, due to the need to avoid signal interference with current commercial satellites, the proposed SpaceX satellite constellation is planned to be at an altitude of around 1,100 km.

As with the present status of geostationary orbit, if non-operational satellites are not removed from the orbital space, the orbit will eventually become crowded, increasing the amount of orbital debris. At lower orbital altitudes of several hundred km, since this is the altitude at which current manned missions operate, there is an increased likelihood of endangering manned missions.

The implementation of a suitable propulsion system on small satellites will provide them with maneuvering capabilities that they currently lack. At altitudes of 400 km or lower, a propulsion system can be used to compensate for atmospheric drag, thus increasing the orbital lifetime of small satellites, while ensuring a relatively short orbital lifetime after their operational lifetime ends. Similarly, a propulsion system can also be used to reduce the orbital altitude of small satellites at altitudes of 500 km or higher near the end of their operational lifetime. This will drastically reduce the time required for a satellite to re-enter the atmosphere, thus mitigating orbital debris. Finally, a propulsion system can also enable small space probes to perform dramatic orbital changes in order to visit and study celestial bodies such as near-Earth objects and the moon.

For propulsion systems for small satellites in the 1 – 10 kg weight range, pulsed plasma thrusters (PPTs) are a promising candidate. They are a structurally simple form of electric propulsion and were the first to be tested in orbit. They were used for attitude control on the Zond-2 spacecraft in 1964.[3]

II. Pulsed Plasma Thrusters

A. Introduction to Pulsed Plasma Thrusters

Pulsed plasma thrusters operate by storing energy within a capacitor, which is then used to ablate propellant using an electric arc, thus producing plasma that is propelled between two electrodes. The capacitor is charged and discharged periodically, resulting in pulsed operation (see Fig. 1). Conventionally, solid propellant is used, and polytetrafluoroethylene (PTFE) has been by far the most commonly used solid. However, PTFE can suffer from issues such as charring of the solid propellant surface and late-time ablation, contributing to lowering of the overall thruster lifetime and the propellant utilization efficiency. Furthermore, as the solid propellant is usually fed into the thruster by spring powered feeding systems, the structure, shape, and layout of a thruster carrying a large amount of propellant mass will be limited by the spring loading design.

Some of the issues with solid propellant PPTs can be resolved with the use of liquid or gaseous propellants. However, the use of gaseous propellants usually requires high pressurization

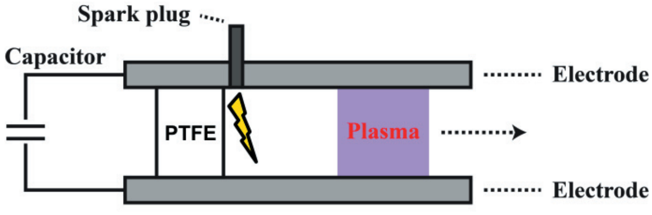


Figure 1. Simplified schematic of a pulsed plasma thruster.

for storage and high-speed valves for propellant delivery. On the other hand, liquid propellants can potentially be stored and delivered using concepts and designs derived from the field of microfluidics. Furthermore, since liquids do not diffuse as fast as gases in a vacuum, the need for high-speed valves is eliminated.[4]

B. History of Liquid-fed Pulsed Plasma Thrusters

A key aspect of liquid-fed PPTs (L-PPTs) is the delivery system of the liquid propellant. An ideal delivery system can provide only the required amount of propellant per pulse, thus increasing the propellant utilization efficiency and eliminating late-time ablation. However, due to the volatility of most liquids in a vacuum, it has been challenging thus far to balance issues such as propellant leakage with efficient conversion to plasma. If volatile propellant droplets are too large and the required evaporation time is too high, a significant proportion of each droplet will instead freeze in a vacuum, thus decreasing the propellant utilization efficiency.

Historically, several different liquids have been tested as propellants using different propellant delivery strategies. The first attempt to use a liquid propellant was in fact the use of the liquid metal mercury by the Royal Aerospace Establishment (RAE) in the late 1960s.[5] They found that the actual propellant utilization efficiency was very low because a great quantity of propellant introduced by the main discharge was wasted. Around the turn of the century, a water-fed PPT design using a passive porous feeding system was investigated.[6-8] It supplied propellant by allowing water to passively diffuse through a porous ceramic material. Different passive mass flow rates were tested by changing design geometries such as the thickness and cross-sectional area of the porous ceramic. A relatively high mass flow rate was necessary to sustain the discharge, resulting in large propellant loss between discharges, which would also result in further propellant loss when the thruster is not operational

Alternatively, droplet-on-demand PPT designs were also investigated at around the same time.[9] It was determined that smaller droplets resulted in better performance, likely due to the improved evaporation rate (due to the increased surface area) for a given volume. Propellant loss is suspected to occur due to incomplete evaporation of the droplets during the PPT discharge time. However, producing smaller droplets with piezoelectric or solenoid valves in a vacuum is difficult, with smaller orifice sizes having a tendency to clog and requiring high pressure differences to drive the production of droplets. A heating system was successfully tested, which improved the PPT performance by improving the vaporization of the liquid propellant droplets.[10] However, in a vacuum, since almost all liquids are volatile at the operating pressure, the liquid droplets exist in a permanent Leidenfrost state due to the constant vaporization of their outer layer. This decreases the heat transfer effectiveness from a hot surface and can result in liquid droplets bouncing off surfaces, thus resulting in only transient heat transfer.

In this paper, we present early results and discussion regarding two different approaches currently being investigated for L-PPTs: ablative liquid-fed pulsed plasma thrusters and electrospray-assisted liquid-fed pulsed plasma thrusters. The former is a passive L-PPT system while the latter is an active L-PPT system. The difference between these is that a passive L-PPT does not allow for control over the delivered propellant mass (such as for a water-fed PPT using a passive feeding system), while an active L-PPT allows for variation in the delivered propellant mass (such as for a drop-on-demand feeding system).

III. Ablative Liquid-fed Pulsed Plasma Thrusters

A. Background

Under the European FP7 program, the L-μPPT project has been developing a PPT using a custom syringe micro-pump and a non-volatile liquid propellant.[11] The propellant, a perfluoropolyether (PFPE) compound, was found to be a promising alternative to PTFE due to its resistance to carbonization at high temperatures and chemical similarity with PTFE. However, in early designs, it was determined that a wetted path of propellant was required between the main electrodes for a discharge to be initiated. Discharge triggering was prevented after depletion of this wetted path.

Here, we will present preliminary results for a basic design of a passive ablative liquid-fed pulsed plasma thruster using a non-volatile liquid propellant similar to that investigated in past research. To simplify the design of the PPT, for this system, we aim to have liquid propellant passively supplied by capillary forces, thus negating the need for a pumping system. Propellant loss when the thruster is not operating is a non-issue since the liquid propellant is non-volatile. With the propellant being in a liquid state, spring feeding systems and large solid propellant blocks are no longer necessary as the propellant should be able to be fed from a reservoir with small tubes using capillary forces.

B. Basic Design

The basic design behind a passive ablative L-PPT is the incorporation of an ablation block composed of a porous ceramic that is itself resistant to ablation (see Fig. 2 in comparison with Fig. 1). A non-volatile propellant is then infused within the block. This propellant is then ablated in the place of PTFE in a standard PPT system. Ideally, the ablation block should be able to refill itself with propellant purely using capillary forces. This also requires connection of the ablation block to a liquid reservoir. Realistically, some back-pressure may be required to match the rate of propellant consumption. However, this back-pressure should not be excessively high or propellant leakage may occur.

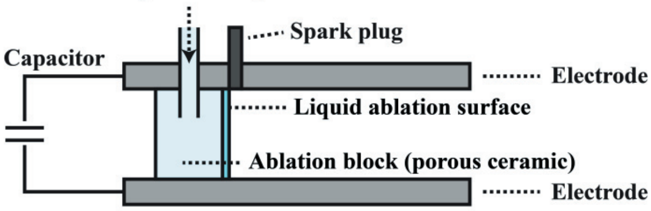


Figure 2. Schematic of a passive ablative L-PPT.

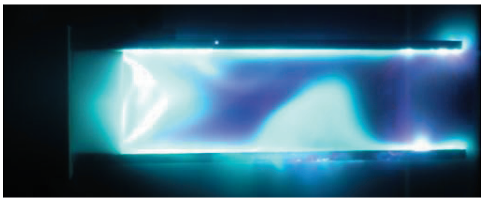
The non-volatile liquid propellant being investigated here is a perfluoropolyether (PFPE), the same family of compounds as that investigated by the L-μPPT project. The ablation block was constructed from porous alumina (Al_2O_3) with an average reported pore size of 1 μm and a porosity percentage of 55.0%. The loading process of the ablation block involved immersion in the liquid propellant in a vacuum in order to remove entrapped air and replace it with the propellant.

C. Results

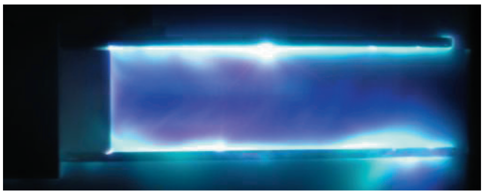
Figure 3 shows long exposure images of single discharges with (a) solid PTFE propellant, (b) an empty unloaded ablation block with no propellant (i.e., a plain porous alumina block), and (c) a loaded ablation block infused with non-volatile liquid PFPE. For all cases, the capacitor voltage was 1.5 kV and the spark plug ignition voltage was 12.5 kV. Immediate qualitative differences are noticeable between the discharge of an unloaded (Fig. 3b) and a loaded (Fig. 3c) ablation block. This suggests that PFPE is being successfully ablated upon loading of the ablation block, while electrode erosion is likely to be occurring without propellant present.

Qualitative energy-dispersive x-ray spectroscopy (EDX) was performed on the unloaded and loaded ablation blocks after several thousand thruster discharges. These are shown in Fig. 4. Figure 4a shows a qualitative EDX spectra of an unloaded ablation block. Figure 4b is a magnification of the >2 keV region in Fig. 4a. Copper deposition was positively identified, confirming that electrode erosion occurred when the ablation block was not loaded with liquid propellant.

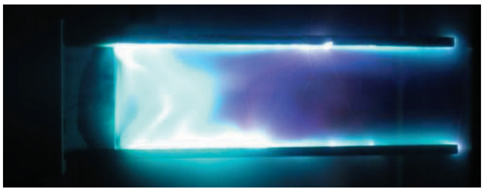
Conversely, Fig. 4c shows a qualitative EDX spectra of an ablation block loaded with PFPE after several thousand discharges. It is notable that copper peaks are no longer readily apparent, indicating that the liquid propellant was successfully ablated instead of the electrodes. Fluorine and carbon were identified, and could be associated with either residual propellant on the surface, or the surface deposition of fluorocarbons.



(a)



(b)



(c)

Figure 3. Long exposure images of the discharge plume of (a) PTFE PPT, (b) empty unloaded ablation block, and (c) loaded ablation block infused with liquid PFPE.

After 5,000 discharges at identical system parameters, solid PTFE was observed to have accumulated a small amount of black charring, likely to be carbon. On the other hand, the surface of the ablation block loaded with PFPE was visibly cleaner than that of PTFE, even though a small amount of discoloration was still observed. This is in agreement with the results observed in the L-μPPT project, but longer term discharge testing is still necessary to determine the eventual effect of the reduced surface deposition that still occurs.

Early indications from our measurements also suggest a higher mass shot with liquid PFPE (~20 – 30 µg) when compared with solid PTFE (~10 µg) at identical system parameters. Further measurements are required, but a passive ablative L-PPT using PFPE may be suitable as a higher thrust variant of the PPT.

We determined that PFPE mass equivalent to around 45% of the original unloaded ablation block's mass was able to be fully loaded within the ablation block (for a 20 x 10 x 10 mm block). Even without attachment to a liquid reservoir, the total infused propellant mass is sufficient for over 50,000 shots. However, this includes the unlikely assumption that all the propellant will naturally migrate to the ablation area. We are currently testing the longer term behavior of this system, but without an applied back-pressure or attachment to a liquid reservoir, it is likely that at some point, there will no longer be sufficient liquid propellant near the surface of the ablation area to be successfully ablated, and it is also likely that this may occur long before all of the propellant mass infused within the ablation block is expended.

In future tests, we will attach a feeding tube to the ablation block in order to test a passive feeding system connected to a liquid reservoir. While not necessary for ground tests, practical implementation will require a liquid reservoir to hold enough propellant mass to perform large ΔV maneuvers. We will also be testing ablation blocks with different pore sizes in order to determine the effect that the combination of pore size and back-pressure has on the behavior of the system.

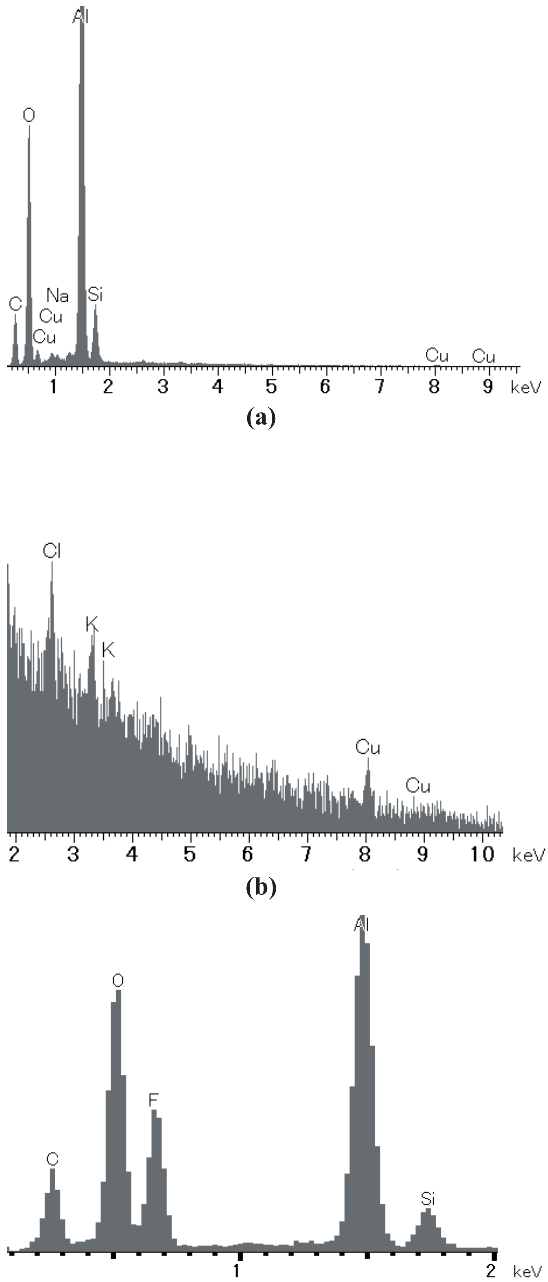


Figure 4. Qualitative energy-dispersive x-ray spectroscopy (EDX) spectra of the ablation surface after several thousand discharges. (a) An empty unloaded ablation block. (b) A magnification of the >2 keV region of an empty unloaded ablation block. (c) A loaded ablation block infused with liquid PFPE.

IV. Electrospray-assisted Liquid-fed Pulsed Plasma Thrusters

A. Background

In contrast to the passive system discussed in the previous section, an active electrospray-assisted PPT is intended to enable control over each mass shot with the use of a liquid injector and a volatile liquid propellant. There has previously been research conducted on the use of electrospraying for microthrusters. A schematic of the basic operation of an electrospray is shown in Fig. 5. To initiate an electrospray, a high voltage difference of several kV is applied between an emitter and a conductive capillary needle through which liquid is fed. Upon the application of a potential difference, liquid at the tip of the capillary needle deforms into a shape called a Taylor cone. Then, depending on the applied voltage, the extracted liquid jet can be whipped violently by the electric field and can break up into extremely small droplets. This has the potential to produce droplets that are several orders of magnitude smaller than the size of the capillary needle.

Colloid thrusters, also known as electrospray thrusters, exclusively employ the electrospray process in microthrusters that can be used for very precise thrust control (in the order of nN) due to their low thrust. More recently, in order to improve the performance of these thrusters, ionic liquids have been investigated as propellants.[12,13] Ionic liquids are salts in a liquid state, and when used in an electrospray thruster, have the potential to produce ion emissions without the formation of any droplets, i.e., ionic mode electrospray. As only ions are extracted, while the specific impulse of these ionic mode thrusters are improved compared to conventional electrospray thrusters, the thrust is further decreased, being in the order of pN for a single capillary. Due to this extremely low thrust, research has been conducted into the use of microelectromechanical systems (MEMS) in the production of multiple emitters in a small area in order to improve the throughput of the thruster.[12-14]

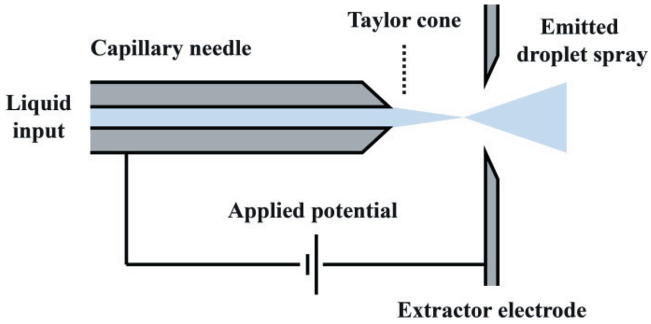


Figure 5. Simplified schematic of an electrospray.

In our research, we aim to leverage the electrospraying process in decreasing the size of volatile liquid droplets fed into a PPT. Since plasma formation will occur during PPT operation, there should be no need to restrict the injector to ionic mode operation, thus allowing more common liquids such as water and ethanol to be investigated. As the electrospraying process is only meant to assist in liquid propellant injection for the PPT, it may be possible to utilize higher flow rates than conventional electrospray thrusters. From past research, the expected size range of droplets produced this way should be in the order of microns and possibly smaller. This is orders of magnitude smaller than droplets produced purely by injection out of an orifice or a capillary.

Similar to passive ablative L-PPTs, this approach also enables a more convenient feeding system compared with solid PPTs. Whereas passive L-PPTs provide no control over the ablated volume and mass shot, an active injector should allow for changes in the mass shot by changing the amount of liquid propellant delivered per discharge. However, this increased control and versatility comes at the expense of a more complicated system with the introduction of an active liquid injector.

B. Basic Design

The basic design of an active electrospray-assisted L-PPT simply includes an electrospray liquid injector (Fig. 6) attached to a conventional PPT without a solid propellant block. However, compared with normal electrospray setups, there are factors involving the use of a PPT that sets limits and bounds on some system variables and design approaches. During our preliminary investigations, we have identified some factors that should be considered when designing such a system.

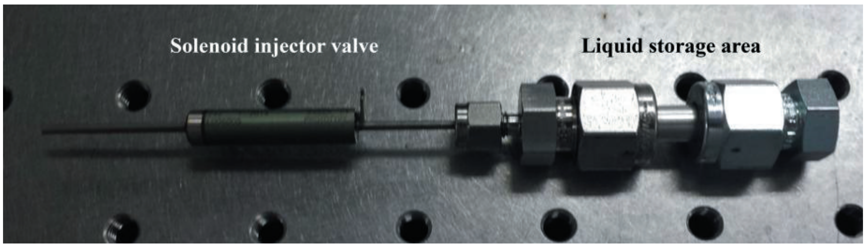


Figure 6. Image of solenoid injector valve and liquid storage for vacuum electrospray. The extractor electrode is not shown. The original outer diameter (shown here) of the exit is 1.6 mm.

C. Recommendations

An independent extractor electrode cannot be used on an electrospray-assisted L-PPT due to the presence of pre-existing charged electrodes on PPTs. This necessitates design compromises instead of simply adding a pre-assembled electrospray injector to a PPT. The extractor electrode and a charged electrode of the PPT should be unified such that they use a common high voltage source, preventing unwanted discharge from occurring between the high voltage source of an independent extractor electrode.

In addition, the grounded electrospray injector capillary needle and valve should be located at a greater distance away from the extractor electrode/charged PPT electrode than the ground electrode of the PPT. This is to prevent discharge from occurring between the electrospray injector and the extractor electrode/charged PPT electrode rather than between the electrodes of the PPT. Therefore, this sets a lower limit for the capillary tip to extractor electrode distance that is dependent on the PPT design.

We have tested electrospray injectors in atmosphere, and are currently working on testing designs that take the aforementioned factors into consideration in preparation for vacuum operation. While the basic system of an electrospray-assisted L-PPT is more complex than that of an ablative L-PPT, as mentioned previously, it should have the capability of control over each mass shot, thus increasing the propellant usage efficiency. This can be done by controlling the injection time of the injector to specify the amount of propellant mass to be injected for each discharge.

On the other hand, if a simple system is desired, an ablative L-PPT can be used to reduce the complexity of the microthruster while still maintaining some of the advantages of liquid propellant such as the ability to passively deliver propellant using capillary forces with tubing connected to a liquid reservoir.

These two very different approaches to liquid propellant delivery have the potential to vastly increase the versatility of L-PPT, and may allow small satellite system designers in the future to select a PPT system appropriate for their requirements after taking into account system complexity vs. the efficiency of propellant delivery.

V. Conclusion

To improve the performance and versatility of pulsed plasma thrusters (PPTs), we are currently investigating two very different approaches in the implementation of a liquid-fed PPT.

The first is an ablative liquid-fed PPT using a non-volatile propellant. Since the liquid propellant is non-volatile, liquid handling in a vacuum is simplified compared with the handling of volatile liquids. However, as the liquid propellant is passively supplied to the PPT, this approach does not allow the mass shot to be directly controlled, similar to conventional solid polytetrafluoroethylene (PTFE) fueled PPTs. Nevertheless, compared to conventional solid PTFE PPTs, there is more versatility available in propellant placement since liquid can be fed via tubes and stored in chambers that can be shaped as needed to fit in the small confines of a small spacecraft, rather than requiring complex spring-fed solid PTFE blocks that have strict requirements in propellant block placement. Early initial data suggests a higher mass shot compared to PTFE PPTs, indicating a higher thrust if all other variables are kept constant. More data will be collected to compare other specifications of the system.

The second liquid delivery approach involves the use of a volatile liquid propellant with an assisting electrospray injector. The electrospray injector is intended to further reduce the size of injected droplets by using the electrospraying process. There are physical restrictions on the placement and operation of the electrospray injector due to the presence of charged electrodes on PPTs. Due to this, it would be preferred that a single common electrode is used as both the charged electrode of a PPT and the extractor electrode of the injector. Compared with the first approach, an active injector allows for the direct control of each mass shot, but results in increased complexity.

These two differing approaches greatly increase the versatility of the basic PPT design. The selection and balance of complexity vs. propellant efficiency will depend on the requirements of each specific spacecraft.

Acknowledgments

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