Characterization and Optimization of Liquid-Ablative and Air-Breathing PPT, Part I: Thrust and Discharge Performance

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Solid PTFE is the standard propellant for pulsed plasma thruster and was until now exclusively used in space. However, achievable total impulse and lifetime are limited by feeding issues with larger propellant blocks. Two approaches are outlined in this study how these limits could be overcome. A liquid and a gaseous propellant underwent a performance and discharge analysis and were compared to the reference PTFE. The liquid, non-volatile PFPE generates on average a 20% higher impulse bit at the cost of efficiency due to a 3–4 times higher mass bit. Its chemical composition allows for a feeding system solely relying on capillary forces. For operation with air, two new coaxial PPT designs are introduced and compared to an air-breathing parallel-plate PPT. It was found, that performance and discharge characteristics vary significantly with each design.

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Nomenclature

ESA	=	European Space Agency
HDPE	=	High-density polyethylene
LVDT	=	Linear variable differential transformer
PCA	=	Pressure control assembly
PEEK	=	Polyether ether ketone
PFPE	=	Perfluoropolyether
PPT	=	Pulsed plasma thruster
PTFE	=	Polytetrafluoroethylene
E_0	=	Capacitor energy
I_{Bit}	=	Impulse bit
I_{Dis}	=	Discharge current
I_{SP}	=	Specific impulse
m_{Bit}	=	Mass bit
U_{Dis}	=	Discharge voltage
p_{Inlet}	=	Inlet pressure
t	=	Time

I. Introduction

Pulsed pulsed plasma thrusters (PPT) are low-complexity electric propulsion systems, which had been applied since 1964 as AOCS thrusters or small satellite main engines.[1–4] The exclusively used propellant on every mission involving PPTs so far was PTFE, commonly known as Teflon™. PPTs operated with PTFE benefit from a simple system design and good ablation behavior. However, the solid state of PTFE leads to feeding mechanisms, which usually consist of springs or similar moving parts.[5] Depending on the required total impulse, propellant feeding can quickly become a problem that significantly raises complexity and defies utilization especially on small satellites. Previous research aimed to account for that problem by using helix or semi-circle shaped PTFE blocks, but those still rely on moving parts to feed the thruster.[6,7]

To extend the application regime of PPT, previous research suggested liquid and gaseous propellants to overcome the feeding issue. The non-volatile liquid propellant PFPE has a similar fluoropolymer composition like PTFE. Its ability to be operated in an ablative PPT promises PTFE like performance with a simple and more versatile feeding system.[8,9]

A second approach is to develop an atmosphere-breathing PPT for satellites orbiting Earth on orbits below 250 km.[10,11] Especially Earth observation missions could benefit from significantly higher resolution or low-cost equipment.

This study compares thrust performance and discharge characteristics of both PFPE and air-operated PPTs with PTFE as reference. Dry air was used as propellant as a first step towards developing an atmosphere-breathing PPT. Hence, the term "air-breathing" is applied within this study. Two additional air-breathing PPT designs are being introduced and discussed in terms of future optimization.

II. Experimental

This study was conducted in the Komurasaki-Koizumi Laboratory of the Department of Aeronautics and Astronautics at the University of Tokyo.

A. Vacuum system

A ∅1 m x L1.5 m vacuum chamber hosted the equipment to conduct all experiments. Operational pressure levels of $5 \cdot 10^{-3}$ Pa were achieved with a rotary vane and turbomolecular pump forming a two-stage vacuum system.

B. Thruster design

In total three PPTs were operated in this study. Aside from the parallel-plate PPT developed during earlier studies,[10,12] two different coaxial PPTs named Asuka and Hägar were designed, manufactured, and operated. All PPTs have the same power supply and 15 µF-capacitor in common, allowing a discharge energy of up to 47 J at 2500 V applied. The designs are each described in detail in the following sections.

Parallel-plate PPT

Based on the experience made with ADD SIMP-LEX, the design features tongue-shaped electrodes diverging at mid-length to shape a 10 deg flare angle at the thruster's end. This design promises an increase in thrust efficiency of nearly 35% compared to simple rectangular plates arranged in parallel.[12] Developed as ablative laboratory model to use PTFE and PFPE as seen in Fig. 1, a special separator was introduced to allow operation with air. The gaseous propellant is fed via a central hole, entering the thruster in the same region PTFE blocks were put before. It shall be noted that no containment to prevent potential losses was added.

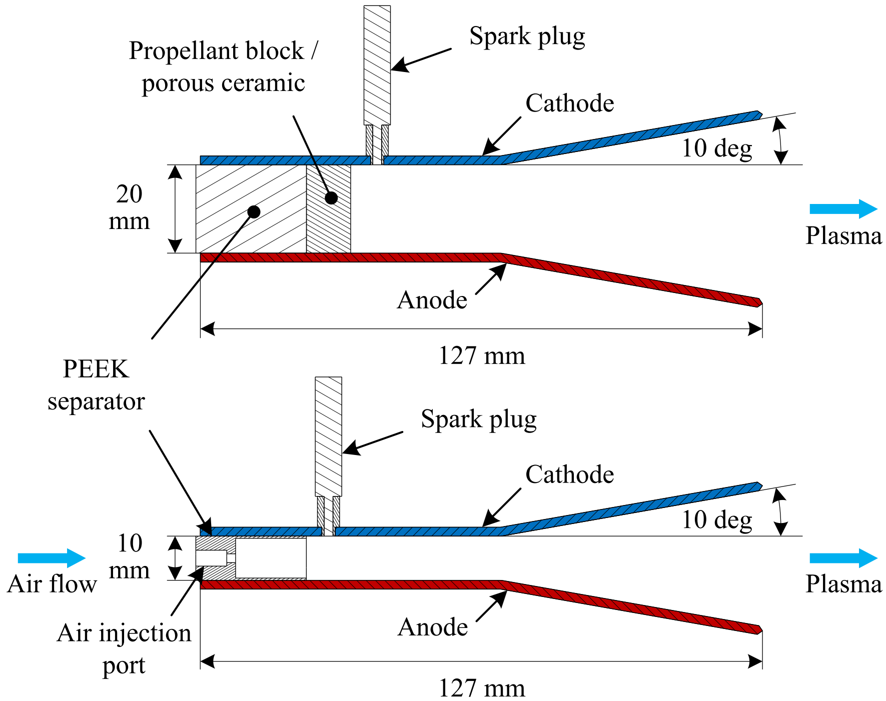


Figure 1. Schematics of the parallel-plate PPT in ablative (upper) and air-breathing configuration (lower).

Coaxial PPT ”Asuka”

Derived from common coaxial PTFE PPT designs,[13] acceleration of the plasma is considered to be dominated by electrothermal effects. For ablative PPTs, it is expected to show better performance at energy levels below 20 J,[14] but no experiments were conducted so far in gas-fed configuration.

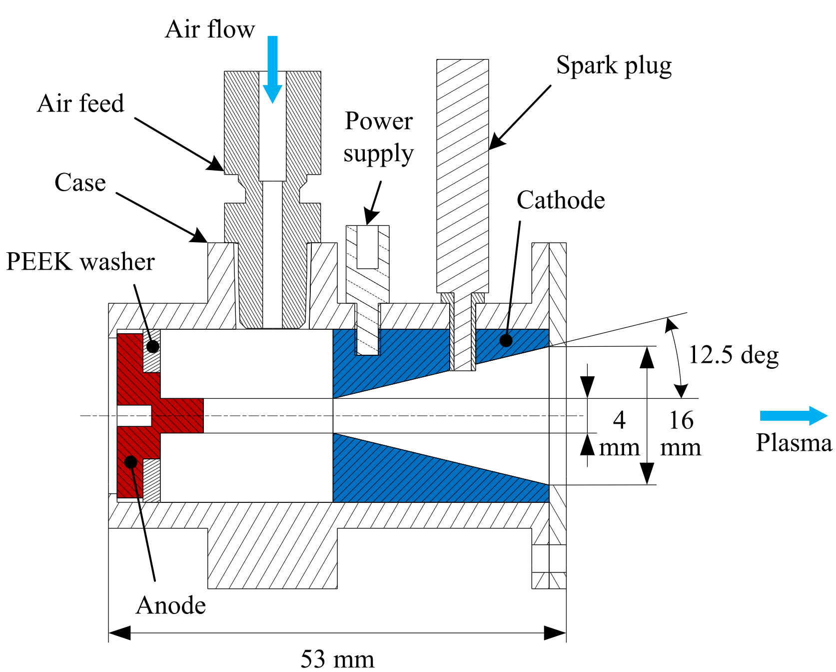


Figure 2. Schematic of the coaxial PPT ”Asuka”.

As it can be seen in Fig. 2, the air enters a cylindrical discharge chamber from a radial direction. Since the air needs to be redirected by 90 deg, the cold gas impulse should be lower but the air stays longer in the chamber, potentially allowing for a better propellant utilization efficiency.

The case is made of high-density polyethylene (HDPE) and sealing is done with a washer made of polyether ether ketone (PEEK) and PTFE tape in the gap between electrode outer surface and case. At the thruster's exhaust side, the cathode forms a 12.5 deg flare angle.

Coaxial PPT "Hägar"

The second coaxial PPT design is more similar to a parallel-plate PPT. Its concentric electrodes presumably lead to a electromagnetically dominated acceleration, especially at energy levels above 20 J.[14]

Coaxial PPT Hägar is designed with similar dimensions as the parallel-plate PPT. In Fig. 3 the axial air injection can be seen. To create a homogeneous air flow inside the discharge chamber, the air enters the thruster via two ports both equipped with porous ceramic inlays. Incident air should be slowed down by the ceramics to gain better propellant utilization efficiency. The spark plug is placed at the same position as in the parallel-plate PPT design to allow for better comparison.

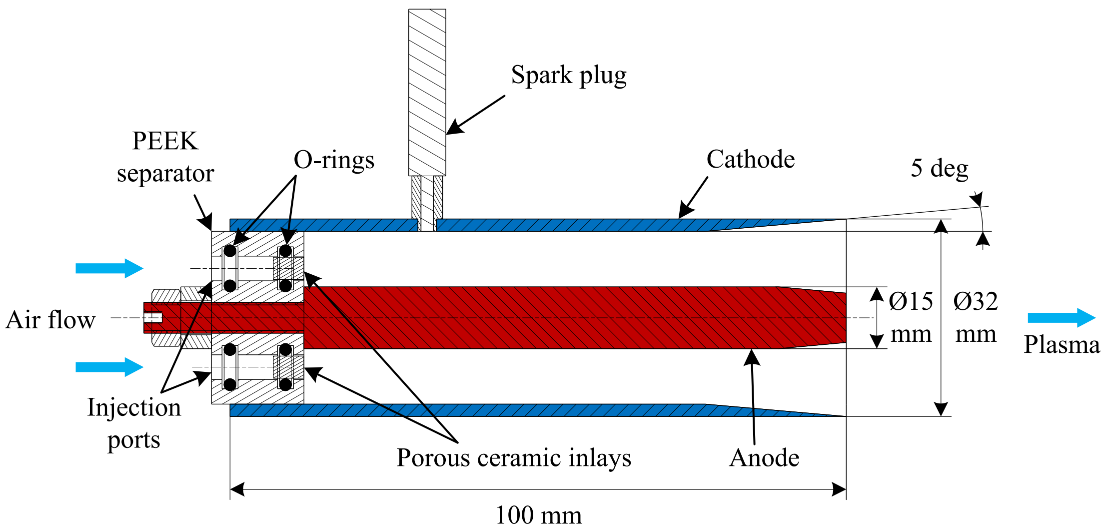


Figure 3. Schematic of the coaxial PPT "Hägar".

C. Propellant

For the propellant comparison using the parallel-plate PPT, each propellant had to be differently supplied. The applied methods are introduced in this section.

The solid PTFE was fed by inserting a 10 mm×10 mm×20 mm sized block between the electrodes.

Liquid PFPE needs a vessel to enable ablative operation. A porous ceramic of the same size as the PTFE block and a pore size of 0.1 µm was chosen for this purpose. By submerging the ceramic in PFPE under vacuum conditions for about 10 hrs, an impregnated propellant block is created. It can then be inserted between the parallel-plate PPT's electrodes. Via capillary forces, the PFPE is fed to the ceramic surface where it forms a thin film layer, which does not evaporated as PFPE's has a vapor pressure of 10^{-4} Pa at 25 °C. After its formation, feeding is blocked preventing initial contamination of the electrodes. This layer will later be ablated like the surface of a common PTFE propellant block.[16]

Dry air is fed via a pressure control assembly (PCA) towards the thruster. A pressurized bottle of dry air marks the main source. Through a pressure regulator and two solenoid valves with a plenum tank in between, the pressure is set to operational level. The plenum tank has a diameter of 10 cm, which is large enough to provide a approximately constant pressure level during the minimum opening time of 5 ms. All air-breathing PPTs were operated using the same setup.

D. Instrumentation

Impulse balance

Impulse bit measurements were conducted with a pendulum type impulse balance shown in Fig. 4. The lightweight design consists of table lying on spike-shaped hinges. Those hinges are attached to three rods, which rest on a supporting frame with the same spikes. All parts are made of aluminum or non-magnetic steel to prevent parasitic effects from thruster operation. The table is design to allow PPTs of different mass and size to be mounted.

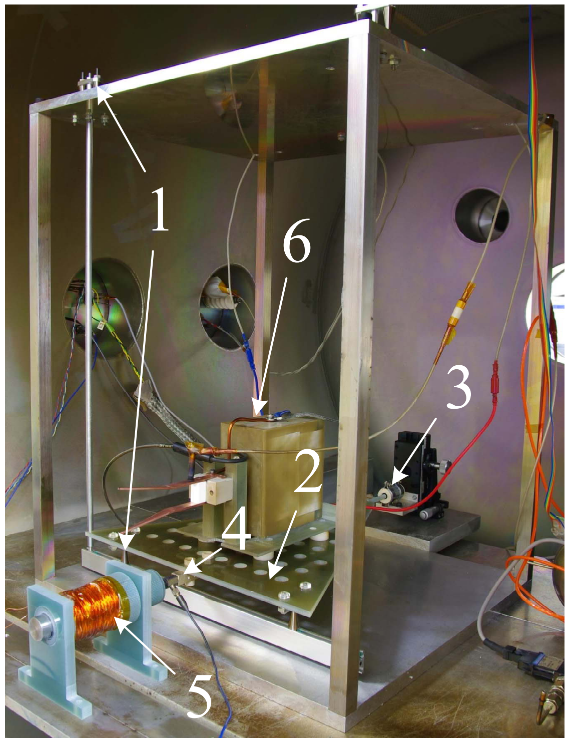


Figure 4. Pendulum type impulse balance at the University of Tokyo (1: Spikes, 2: Table, 3: LVDT, 4: Force transducer, 5: Electromagnetically actuated hammer, 6: PPT.)[17]

Performance analysis is done by recording the displacement excited by a pulse and correlate it to an impulse. A linear variable differential transformer (LVDT) serves as displacement sensor. The system is calibrated by an electromagnetically controlled hammer that hits a piezo-electric force transducer attached to the table.

A resolution of 50 µNs was achieved with the parallel-plate PPT mounted, which weighs about 2 kg.[18]

Mass bit measurements

The measurement methods of mass bits differed between the propellants. For ablative operation, the propellant block and electrodes were weighed prior to 1000 pulses and again afterwards with a Sefi IUW-200D high precision scale. Influences of incident air after pressurization were determined and calculated into the uncertainty.

For air operation, the pressure level inside the PCA was observed for each shot. The pressure drop during injection was used to calculate the mass bit.

Discharge measurements

To characterize the discharge properties, the voltage and current have to measured during the discharge. A differential probe was used to record the voltage. The current measurements were conducted with a Rogowski coil wrapped around a straight conductor between cathode and capacitor. Since the output voltage is proportional to the current's rate of change, an integrator unit conditions the signal to provide the actual current flow.

E. Test matrix

The experiments were separated in two main campaigns, propellant and air-breathing PPT design comparison. All three propellants were investigated using the parallel-plate PPT in ablative and air-breathing configuration. Impulse performance and discharge characterization were conducted over the capacitor energies range up to 47 J, by changing the applied voltage level. PFPE experiments were limited to 41 J, since self-induced discharges occurred at higher discharge energies. A potential cause might be excessive PFPE, which can be reduced by changes in propellant block geometry and pore size.

During air-breathing PPT comparison, all three designs were operated at 47 J with varying injection pressure in the range of 1–19 kPa. The spark plug was not used in this performance study, since it was not yet possible to properly determine the delay between valve opening and occurrence of air in the discharge chamber.

III. Results and discussion

A. Propellant comparison

To analyze the propellants, impulse bits (Fig. 5) and mass bits (Fig. 6a) were measured and the resulting specific impulse calculated (Fig. 6b). Error bars indicate the uncertainty of each measurement. The impulse bit's uncertainty was calculated via Gaussian error propagation including the standard deviation of five measurements per energy level and the sensors noise. Mass bit measurements were also calculated with Gaussian error propagation, based on standard deviation and uncertainty factors of the precision scale.

For air, cold gas and PPT-operated impulse bits were recorded. By subtracting the cold gas impulse bit from the discharge one, the actual impulse bit resulting from electromagnetic acceleration was deduced. The inlet pressure was set to 19 kPa, which allowed a discharge at the lowest energy level of 6.7 J.

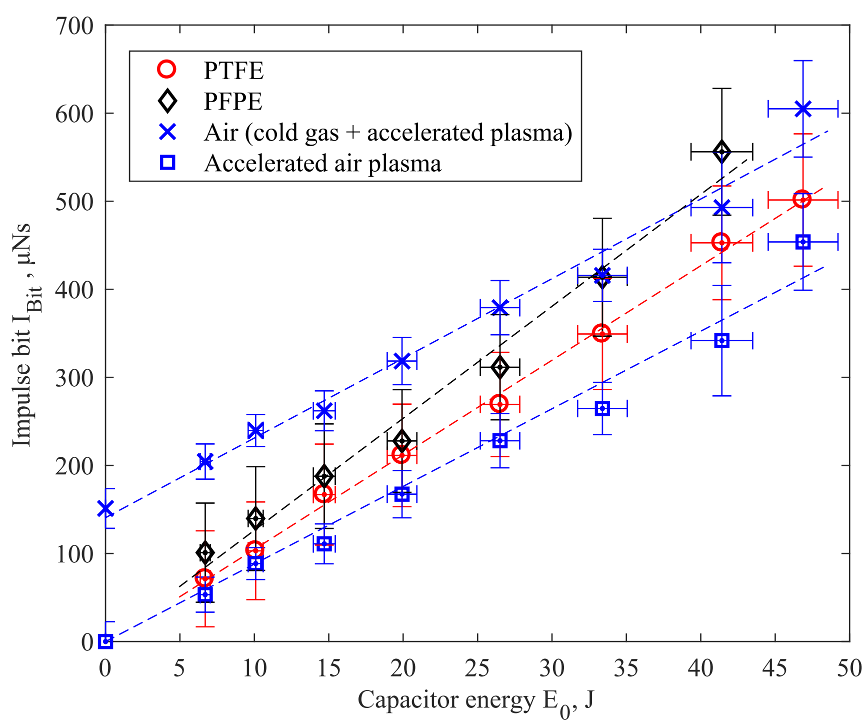
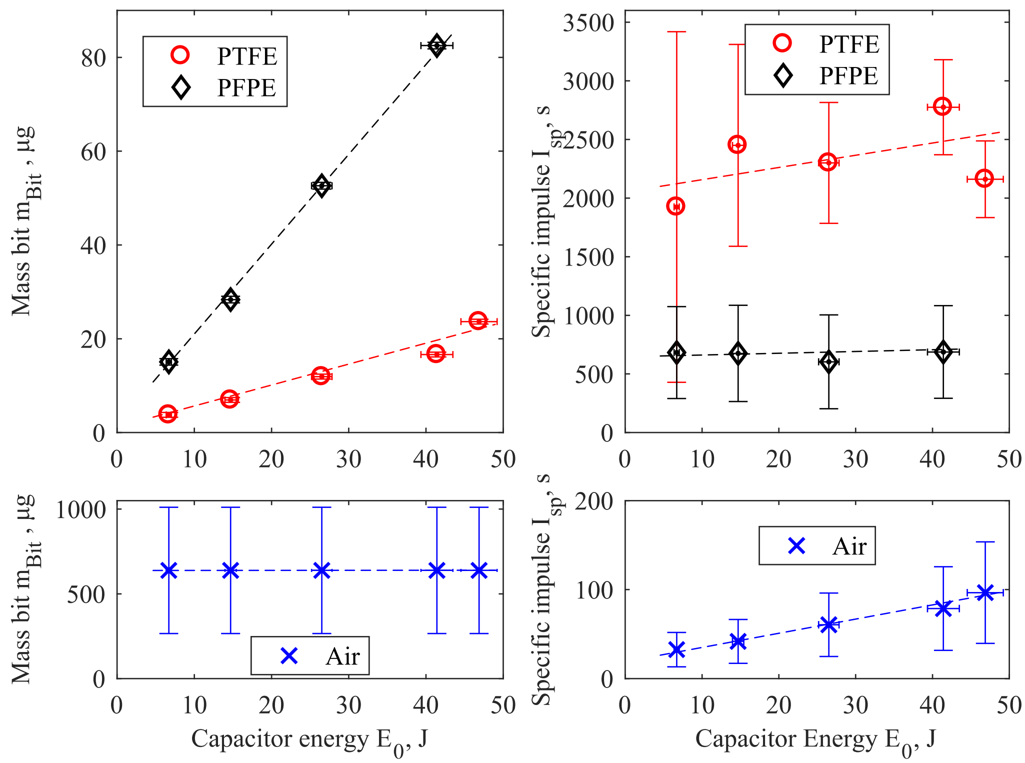


Figure 5. Impulse bit against capacitor energy for PTFE, PFPE, and air.



(a) Mass bit measurements **(b) Specific impulse**

Figure 6. Mass bit and specific impulse against capacitor energy for PTFE, PFPE, and air.

Compared to the reference trend line of PTFE with a slope of 10.7 µNs/J, PFPE and air differ visibly. PFPE shows a steeper behavior with 12.7 µNs/J, whereas air is less inclined than both with 9 µNs/J. The impulse bits of PFPE are approximately 20% stronger than of PTFE, which only becomes significant at higher energy levels. Since the mass bit of PFPE is 3–4 times larger compared to PTFE, as seen in Fig. 6, the difference in impulse bits is most likely caused by increased propellant consumption. Hence, the specific impulse is far lower with values slightly above 500 s for PFPE. PTFE on the other hand is within the expected order of around 2500 s.[14] A PFPE operated PPT at Institute of Plasma Physics and Laser Microfusion, Warsaw was featuring an I_{SP} of 1400 s at 1.25 J,.[19] The capacitor energy was, however, about five times lower compared to the lowest energies in this study. Even though, the results lead to the conclusion that the PPT design, original created for PTFE use, is not optimal for PFPE and optimization is necessary. Refer to "Part II: Spectroscopic Investigation" for further information on that topic.[15]

Air impulse bits at energies < 20 J are dominated by cold gas impulses. Only at higher energy levels, the impulse generated by the accelerated plasma is significantly larger. With a calculated mass bit of 638 µg, air specific impulses are extremely low at around 20–50 s. That is even lower than a common cold gas thrust with 74 s,[20] which is no surprise as the thruster design does not have the shape of a nozzle translating energy via expansion. It shall be noted that due to the large uncertainty of the pressure sensor, the error in mass bit is approximately 50%.

Looking at the discharge characteristic in Fig. 7, discharge current behaves very similar for each propellant with a slightly higher damping during air operation. The discharge voltage of PTFE and PFPE show an almost identical progression, however, the curve for air noticeably differs from ablative operation. The signal seems to be highly damped, but yet no theory was found to explain this phenomena. Differences in acceleration mechanisms between ablative and gas-fed PPTs might lead to an explanation of the discharge behavior.[21]

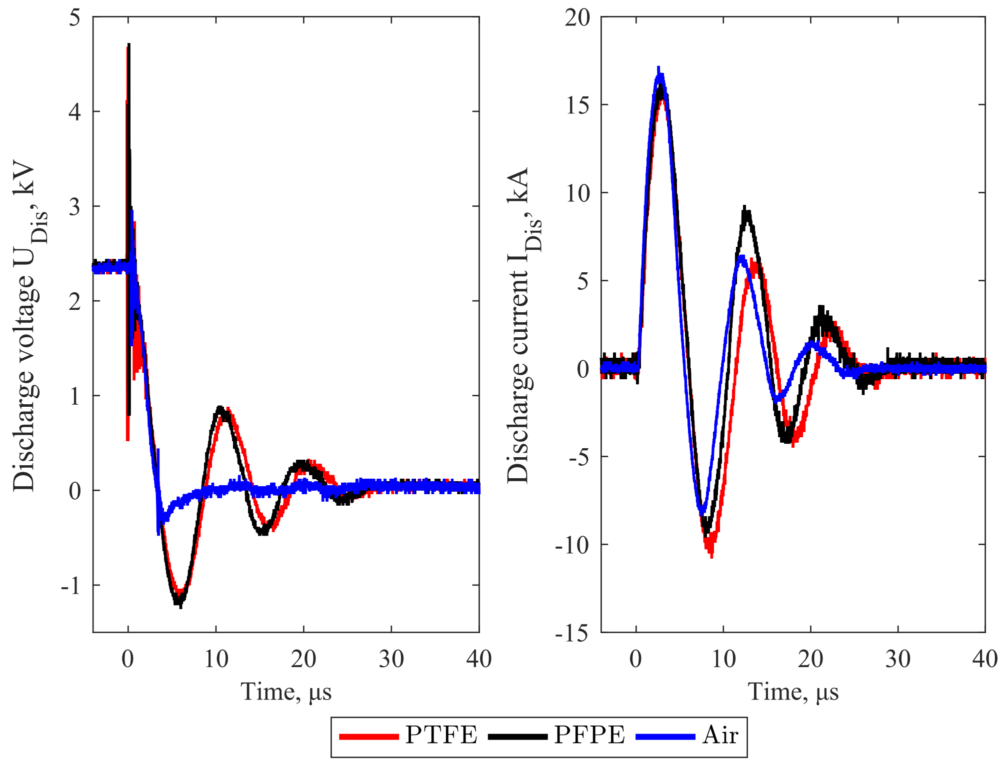


Figure 7. Discharge characteristics of all propellants with voltage on the left and current on the right side.

B. Air-breathing design comparison

The inlet pressure level set for the propellant comparison was as the results show not only unfavorable in terms of efficiency, but is also not realistic. Even facilitating an appropriate air-intake,[22] inlet pressure order of magnitudes around 1 mPa are to be expected.[11,23] Since the high inlet pressure was set to match the low discharge energy, the latter was set to 47 J and the pressure lower to each thruster designs minimum.

The results in Fig. 8 show a similar performance of coaxial PPT Asuka and the parallel-plate PPT. Coaxial PPT Hägar shows an on average 50% lower impulse bit compared to the others. As expected, the cold gas impulse bit is higher for coaxial PPTs, since radial losses occur at the parallel-plate PPT's sides due to a lack of confinement. The lowest pressure level was reached with coaxial PPT Asuka at 2.1 kPa.

The impulse bit of accelerated plasma for each PPT design stays almost constant over the pressure range with a slightly positive slope towards lower pressure levels. Coaxial PPT Asuka shows the most significant one with 5.11 µNs/kPa. The slope might be caused by electrode erosion, which is under investigation. A potential conclusion might be that the mass bit of ionized air is constant over the pressure range at the given capacitor energy of 47 J and applied voltage of 2500 V, hence, resulting in a constant impulse bit. This matter is further discussed in "Part II: Spectroscopic Investigation".[15]

The reason for Coaxial PPT Hägar's comparably low performance most likely lies in the feeding system. It was designed to create a homogeneous cloud around the cathode. Optical inspection revealed that the discharge occurs at only a single spot. The voltage caused a break down in the region with the best product of pressure and distance according to Paschen's law. Most of the air was not ionized and not accelerated, resulting in the low impulse bit.

At the lowest pressure level of 2.1 kPa coaxial PPT Asuka reaches already an I_{SP} of 720 s. This would confirm the theory that better propellant utilization efficiency can be reached at lower inlet pressure levels. This is in accordance with results from Princeton, where high values in the range of 1400–6000 s were recorded with argon in a pressure range of 0.013–1.3 Pa and a capacitor energy of 4 J.[24]

In Fig. 9 the discharge waveforms of voltage and current are displayed at the lowest common pressure level of 11 kPa. It can easily be seen that coaxial PPT Hägar shows a much lower damping coefficient compared to the other designs. This reveals another reason for the low performance, since conveyed energy

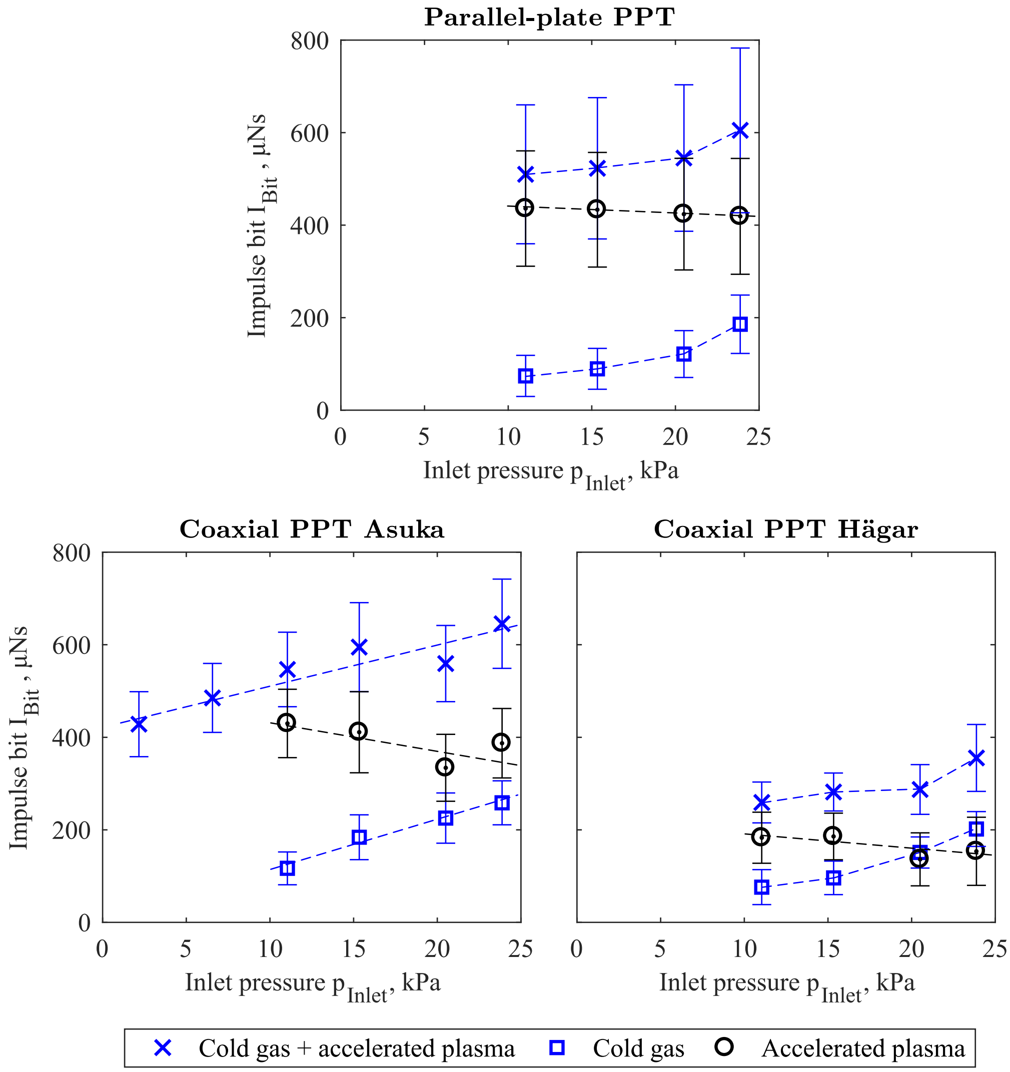


Figure 8. Impulse bits against inlet pressure level of the air-breathing parallel-Plate PPT and coaxial PPTs.

to the plasma was less.

The abnormal behavior of discharge voltage at the parallel-plate PPT does not occur here. At higher pressure levels, the air might have caused a short circuit between cathode and another potential, but at 11 kPa this is not possible anymore.

IV. Conclusion

The liquid and gaseous propellant alternatives PFPE and air were successfully operated. During air-breathing operation, two new designs were successfully tested and characterized.

PFPE shows a higher impulse bit than PTFE at the cost of a 3–4 times higher mass bit. The resulting low I_{SP} proves that the parallel-plate PPT originally designed for PTFE needs further optimization. A smaller ablation area or change in pore size might be an option. Alternatively, the PFPE PPT could be improved towards a high-thrust PPT compensating the lower efficiency with a more versatile and simple propellant feeding system.

During air-breathing experiments, coaxial PPT Asuka proved to be superior and further development should be based on this design. The good performance of the parallel-plate PPT with air could also lead to a design featuring a confinement. In either case, plasma diagnostics have to be conducted to precisely

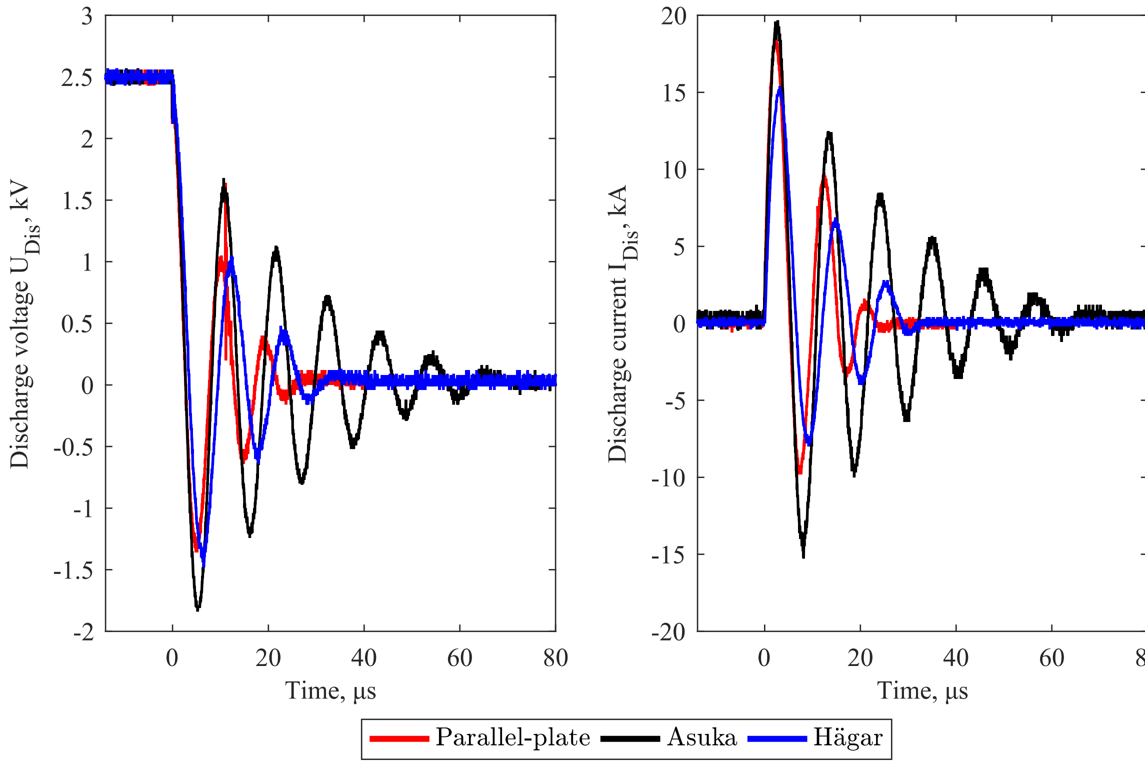


Figure 9. Discharge characteristics of all PPT designs with voltage on the left and current on the right side.

determine the timing of incident air. Finding an operation point where air consumption is confirmed will allow usage of the spark plug, which should significantly lower the achievable inlet pressure. This was done in "Part II: Spectroscopic Investigation".[15] Furthermore, it needs to be investigated, if changes in air composition towards an atmosphere-breathing PPT have noticeable influence on the thruster's overall performance.

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