Characterization and Optimization of Liquid-Ablative and Air-Breathing PPT, Part II: Spectroscopic Investigation

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Pulsed Plasma Thrusters are highly suitable propulsion systems for cubesat propulsion and AOCS tasks of medium-sized satellites, where the required total impulse is rather low. The simplicity of the solid PTFE propellant yields a compact, simple, and lightweight thruster design with no needs for valves and piping. However, with regard to missions with higher total impulse requirements, the propellant feeding of the solid propellant becomes complicated, eventually limiting the possible application.

To extend the application regime of PPT, two new approaches were suggested previously: the use of the non-volatile liquid polymer PFPE in an ablative PPT setup, and the use of residual atmosphere in a gas-fed PPT configuration. This study aims to characterize the two propellants with respect to the standard PTFE thruster, to identify optimization potential, and to understand the plasma behavior in the discharge better.

Plasma creation and acceleration in pulsed plasma thrusters are essential aspects for PPT performance. To understand better how the impulse performance (see part I of this study) is correlated with a change in operational conditions, optical emission spectroscopy is used to study the differences in the emission spectra for the various propellants. For various conditions in discharge energy and injection pressure (for air-fed PPT), and for different positions in the plasma, the spectra are discussed with respect to observed spectral lines, ionization levels of the particle species, and estimated excitation temperatures.

The comparison between PTFE and PFPE is limited to an identification of observed species and of ionization levels over the energy range. Resulting from the chemical similarity, the observed phenomena are matching. Comparable emission intensity levels and ratios of ionization levels indicate a similar amount and composition of charged particles for both propellants. For air-fed PPT, as was inferred from the impulse measurements (part I), the spectra support that ionization is hindered at high injection pressure levels. Neutral

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species and low excitation temperatures were observed. With a reduction of pressure, emission lines of higher ionization levels show increased intensities, and the derived excitation temperatures are increased.

Nomenclature

ESA	European Space Agency
HDPE	High-density polyethylene
LTE	Local thermal equilibrium
PEEK	Polyether ether ketone
PFA	Perfluoroalkoxy alkanes
PFPE	Perfluoropolyether
PPT	Pulsed plasma thruster
PTFE	Polytetryfluorethylene
I_{rel}	Line intensity relative to the middle position of the coaxial PPT
I_{Middle}	Line intensity at the middle position of the coaxial PPT
$I_{Top/Bottom}$	Line intensity at the top/bottom position of the coaxial PPT

I. Introduction

The pulsed plasma thruster (PPT) is one of the oldest concepts among electric propulsion systems. First being used by Soviet engineers on the Zond 2 spacecraft in 1964, it has found its place as AOCS thruster in many satellites over the years[1]. The most common design of a PPT that has been used for decades features a solid propellant, usually PTFE, which is ablated in a pulsed arc discharge and accelerated electromagnetically for thrust generation. While this design features a simple setup with a high reliability, it has limits concerning overall achievable impulse, mostly due to difficult feeding of the solid propellant. As a solution to this limitation, liquid and gas-fed PPTs have been proposed and investigated in the past[2–5]. For liquid-fed PPT, the liquid polymer PFPE is an interesting and promising candidate because of its possible simple feeding through capillary forces, and due to the fact that it is already space qualified as a lubricant.

For use in satellites that are to be placed in a VLEO (below 250 km of altitude) orbit, for example for Earth observation purposes, an air-breathing PPT utilizing the residual atmosphere in its orbit as propellant is examined in this paper. Spacecraft in comparably low VLEO heights are subject to a drag force exerted on their fairing caused by the residual atmosphere. To attain a viable mission length, a propulsion system is necessary to compensate the aforementioned drag force. At present, this high invest for a mission, while still providing only a comparably short mission time often prevents the realization of satellite missions in VLEO. Providing a thrust level high enough to compensate for the spacecraft's drag, an atmosphere-breathing propulsion system would enable missions in VLEO without time constraints by limited propellant availability.

This paper uses optical emission spectroscopy to determine the plasma characteristics of a parallel plate PPT able of using either PTFE and PFPE, and a coaxial PPT utilizing dry air. Measurements are carried out at various different energy and pressure (only for air-breathing PPT) levels to derive information about the species present in the plasma, their ionization levels, and estimated excitation temperatures.

For the investigation purposes, this paper introduces the utilized thrusters as well as the experimental setup before discussing the results of the conducted measurements.

II. Experimental

A. Vacuum system

The experiments were conducted in a cylindrical vacuum chamber of the dimensions $\varnothing 1\,\mathrm{m} \cdot \mathrm{L}1.5\,\mathrm{m}$ equipped with a rotary and a turbo-molecular pump. This assembly enables an ultimate pressure of $5 \cdot 10^{-3}$ Pa. The vacuum level the equipment is able to maintain during operation is around $1 \cdot 10^{-2}$ Pa.

B. Thruster Design

In this study two different PPTs were operated, one parallel-plate PPT for the solid and liquid propellants PTFE and PFPE, as well as one coaxial PPT for the air-breathing experiments. During the course of the experiments, the same power supply and 15 µF-capacitor were used. Discharge energies of up to 47 J at 2500 V were applied.

1. *Parallel-Plate PPT for PTFE and PFPE*

The parallel PPT used in this paper has been developed at The University of Tokyo during the course of multiple theses[6,7] and is the same one that has been introduced in detail in part I of this study[8]. Its schematic design can be seen in Fig. 1. It consists of two copper electrodes, a spark plug located in, but insulated from, the cathode and a Polyether ether ketone (PEEK) separator between the electrodes. The propellant is added in block-form between the electrodes directly in front of the separator. A propellant area of $200\,\mathrm{mm}^2$ is exposed to the discharge.

For both propellants, PTFE and PFPE, this identical setup was used. To alternate between the propellants, the PTFE propellant block was exchanged with a porous ceramics block drenched with PFPE, and vice versa. To prevent contamination by any residual propellant, the PPT was thoroughly cleaned with ethanol and the electrodes were polished before inserting the new propellant.

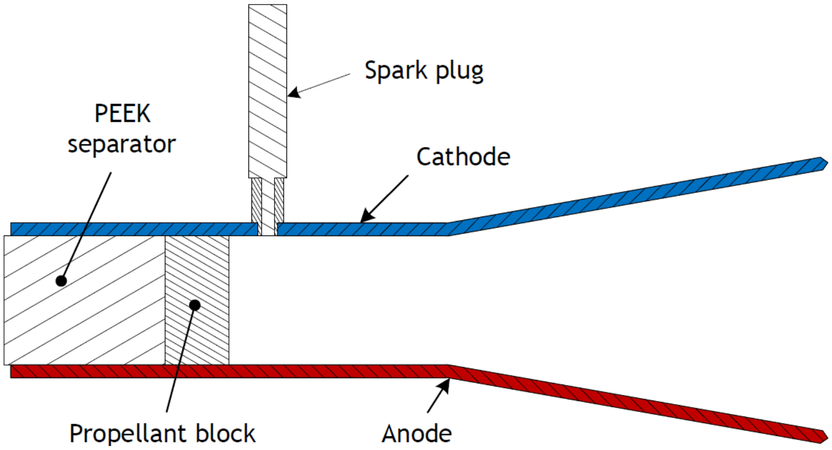

Figure 1. Schematics of parallel PPT[6]

2. Coaxial PPT "Asuka" for Air-Breathing Experiments

For air-breathing operation, a coaxial PPT developed during previous research at the University of Tokyo[6] has been improved and used. The design of a coaxial thruster for operation with air has been suggested by previous research[7], because it was expected that its geometrical containment of the air would prevent radial losses and yield a stronger impulse. The schematic design of the air-breathing PPT is shown in Fig. 2.

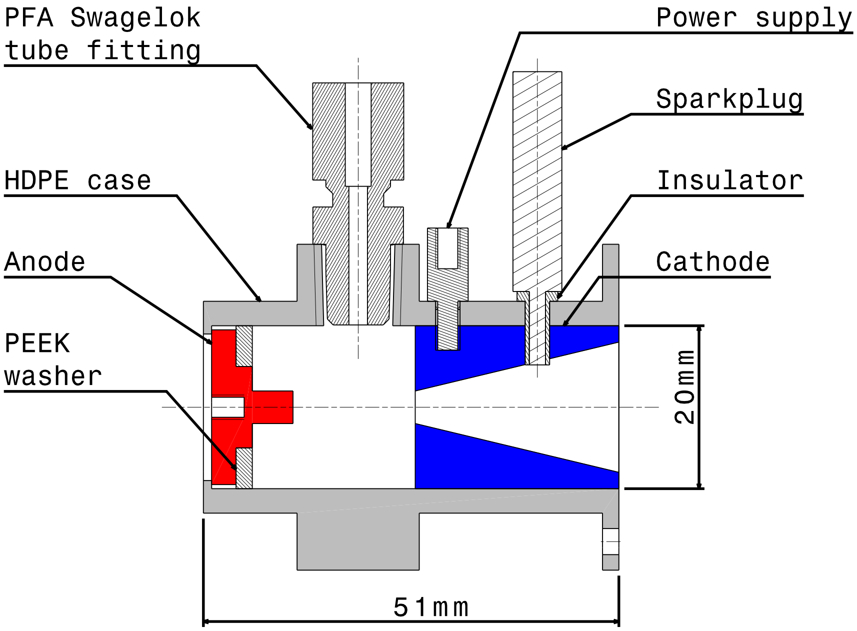

Figure 2. Schematic of the air-breathing PPT.

The thruster is composed of a main high-density polyethylene (HDPE) case with an axially symmetrical copper anode and cathode, wherein the anode is located at the back end of the thruster, and the cathode at its front. The air is fed to the thruster radially into a cavity between anode and cathode. To avoid a discharge over the air-feed system, an inlet made from Perfluoroalkoxy alkanes (PFA) was chosen. To control and time the ignition by a high-voltage spark plug, a LabVIEW software is used.

C. Pressure Control Assembly

For the measurements of the air-breathing PPT, to enable measurement of pressures in a defined operating range and to ensure the controlled injection of air into the thruster, a setup capable of reliably producing the desired inlet pressures and inlet durations has been set up. It features two high-speed solenoid valves with minimum opening times of 1.5 ms, a Pirani-type pressure sensor with a lower pressure limit of $1 \cdot 10^{-2}$ Pa, a sub-tank of within the vacuum chamber to maintain a near constant pressure during injection; and a bottle of pressurized dry air with a pressure regulator. The complete setup with all parts in operational state can be schematically seen in Fig. 3. The propellant is fed from the bottle of pressurized dry air through the pressure regulator to the sub-tank. To set the desired pressure inside the sub-tank, the two solenoid valves are manipulated with a LabVIEW program to increase or decrease the pressure. To create a discharge, the capacitor is charged, the air is injected, and an ignition is triggered by the spark plug.

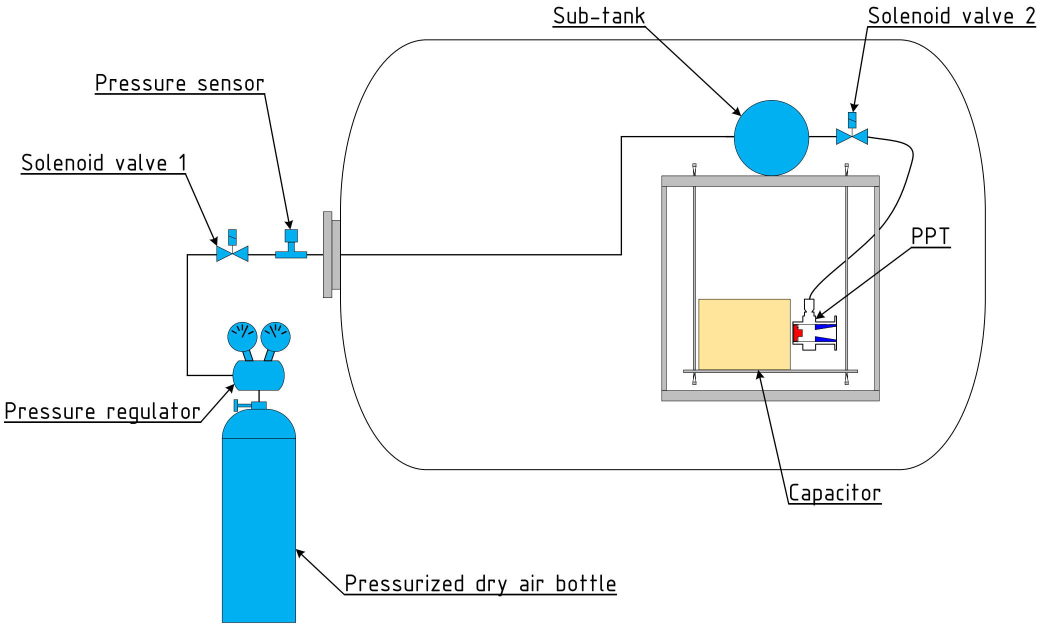

Figure 3. Schematic pressure assembly

At present, the introduced setup is capable of achieving a reproducible injection pressure as low as 5 Pa.

D. Optical Emission Spectroscopy Assembly

An Aryelle 200 spectrometer by Lasertechnik Berlin, Germany, is used for the experiments. Its detailed information is given in Table 1. To ensure the validity of the recordings, a wavelength calibration and intensity standardization are carried out before the experimental campaign. The spectra are recorded with

Table 1. Properties of the spectrometer Aryelle 200.

Aperture	$f/10$
Spectral resolution capability	$7,000 - 15,000$
Max. wavelength range	$175 - 1,100$ nm
Simultaneous inspection range	up to 600 nm
Typ. wavelength range	$210 - 800$ nm
Resolution FWHM	$23 - 90$ pm

an iStar DH734-18F-03 ICCD camera by Andor Technology that is connected to the spectrometer. A PC is used to control the experimental settings and record the experimental data. To correctly and timely trigger the recording of the spectrometer, a shutter controller is integrated into the setup. The schematic setup is depicted in Fig. 4. To focus the spectrometer on the correct region of the plasma plume that is to be investigated, two aspherical lenses with a focal length of 800 mm, and 400 mm respectively are used.

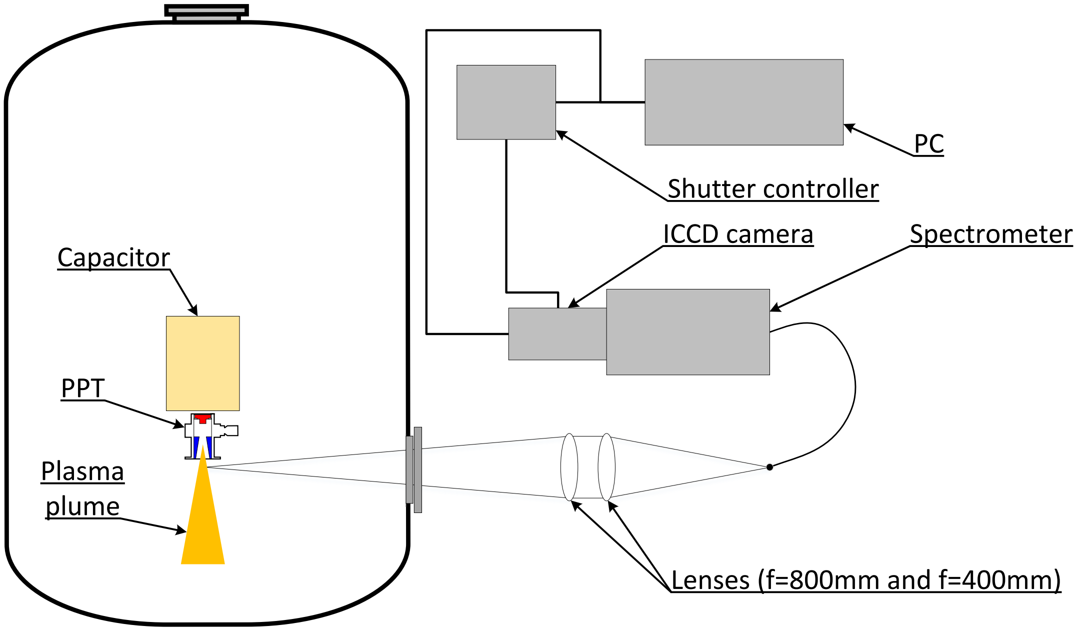

Figure 4. Schematic spectroscopy assembly

E. Test Matrix

The experiments were conducted in three main campaigns. Two campaigns were carried out with the parallel-plate PPT, one with the solid PTFE propellant, and one with the liquid PFPE. Within these campaigns, the voltage of the capacitor was varied between 0.75 and 2.5 kV in 0.25 kV steps, resulting in an energy range of 6.4 to 47 J. For the air-breathing campaign not only the discharge energy, but also the influence of the injection pressure was investigated. The part of the campaign concerning the discharge energy was conducted at the same energy levels as with the parallel-plate PPT at a constant injection pressure of 7500 Pa. This pressure was chosen because it was the lowest pressure that enabled a reliable ignition without using the spark plug. Concerning the variation of the injection pressure, the experiments were carried out at the maximum energy of 47 J at the injection pressure levels given in Table 2. The plasma plume of the coaxial air-breathing PPT was investigated at three different positions, in the middle of the plume and with a vertical shift of ± 5 mm, all 10 mm in front of the PPT's nozzle. All individual measurements were carried out three times at the same settings and then averaged.

Table 2. Injection pressure levels for coaxial PPT experimental campaign

Pressure/Pa	11000; 8800; 6500; 4300; 3000; 1000; 500; 250; 150; 100; 50; 5

III. Results and Discussion

The directly achieved results from the measurements are the complete spectra recorded by the spectrometer's camera. These spectra are then analyzed, the individual lines are fitted with a Voigt-function to determine their true intensity and wavelength, and the individual lines' data and information about the species causing it is taken from the NIST database[9]. In the following sections, the results of the direct experimental data's revision are elaborated and discussed.

A. Comparison Between PTFE and PFPE

A first simple comparison between the two propellants can be carried out by regarding the energy levels at which spectral lines of higher ionization levels can be found, and how many lines of the respective species could be detected. From this information conclusions about the energy transfer into the plasma and the general ionization behavior can be drawn. In Fig. 5 and Fig. 6, the number of identified carbon and fluorine lines in each excitation level for both propellants are displayed, respectively. Judging by the experimental data, both propellants behave very similarly. The number of identified lines of each species do not have significant variations, and more highly ionized species are first detected at the same energy levels with both propellants. Previous studies at The University of Tokyo with the same basic equipment[6] have shown that with similar properties, the mass bits of PFPE are up to four times higher than those of PTFE. Therefore it was expected that more of the avaliable energy was used for ablation, and less for ionization, which would have resulted in lower detected ionization levels in the PFPE plasma. This notion has to be reevaluated, since the expected behavior has not been confirmed by the obtained data.

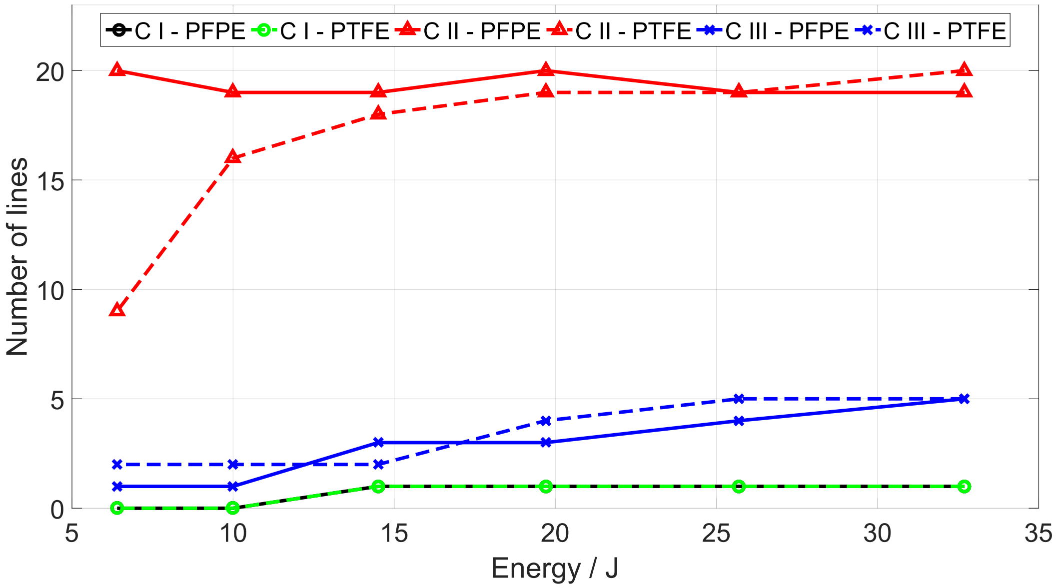

Figure 5. Number of detected carbon lines in each excitation state (bold lines → PFPE; dashed lines → PTFE)

An additional way to compare the two propellants is by comparing the absolute intensities of the detected lines between the two propellants. This yields a relative quantitative statement of the number of particles responsible for creating the spectral line.

An exemplary intensity comparison of a prominent C II and C III line that represent the general tendency is provided in Figs. 7 and 8 respectively. The presented intensities have been fitted, integrated, and normalized.

The obtained results indicate a general tendency of PFPE toward higher ionization levels, compared to PTFE. The intensities of C II are higher for PFPE at low energy levels, where only small amounts of C III are created (see Fig. 5), and the C III intensity is greater almost over the entire range of energies. Moreover, the different gradients of the C II intensity for the two propellants add another indication for a different energy transfer into the plasma. At higher energies, the difference in the C III intensities starts to diverge more strongly, which coincides with the comparative diminution of the C II intensity.

Overall, the two propellants show a similar plasma behavior, with a tendency towards more highly ionized species at high energy levels for PFPE. It has however to be noted, that this similarity also includes the comparative number of ionized particles, although the mass bit of PFPE is significantly higher that that of PTFE[6]. This leads to a very poor propellant utilization efficiency and weight specific impulse of PFPE,

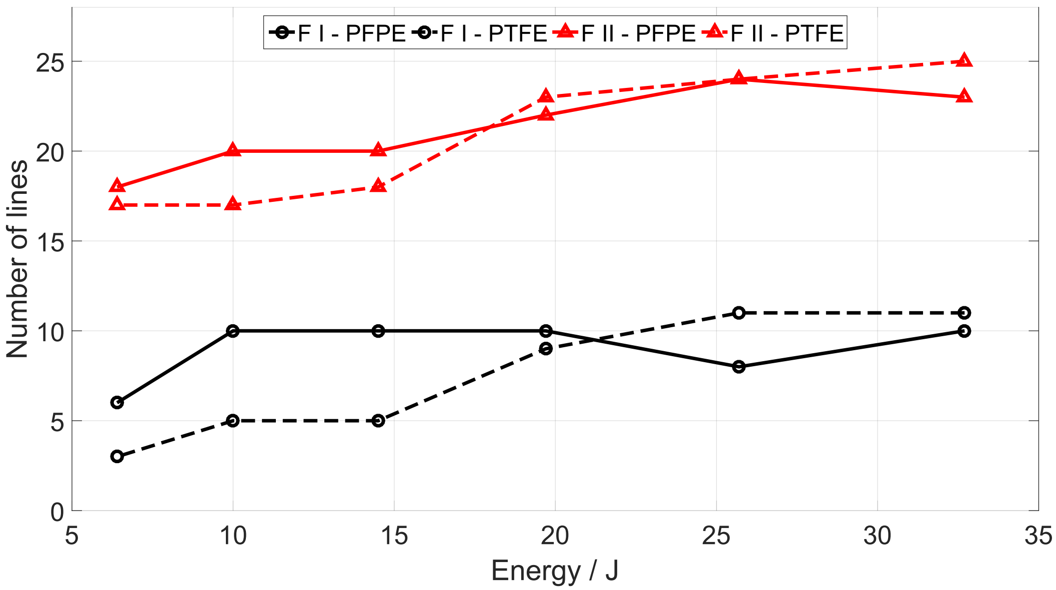

Figure 6. Number of detected fluorine lines in each excitation state (bold lines → PFPE; dashed lines → PTFE)

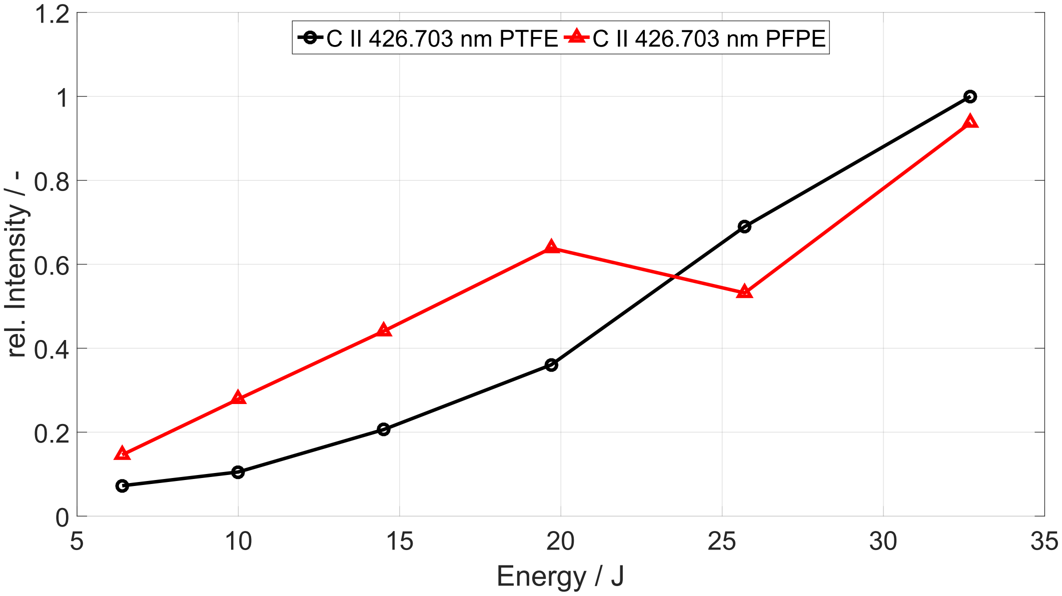

Figure 7. Comparative intensity development of C II at 426.703 nm

which was already discovered in[6] and has been elaborated upon in part I[8] of this study, but could not be explained at that point in time. The results presented herein recommend further research into the details of PFPE's plasma creation and energy transport into the plasma.

B. Air-Breathing Propulsion

To provide a simpler overview over the various correlations investigated, this part is divided into multiple subsections focusing on one correlation each.

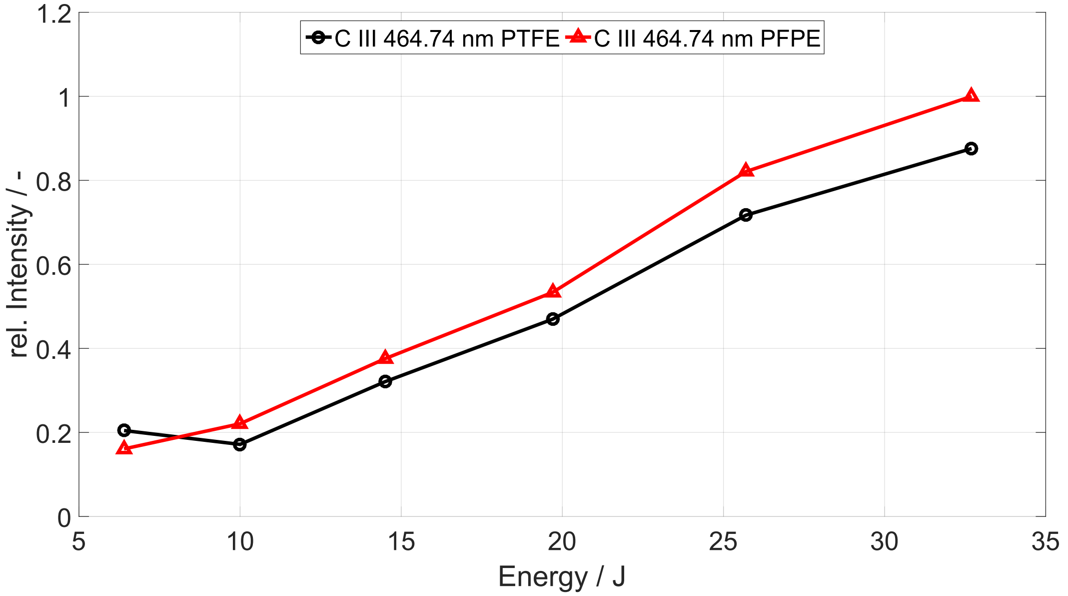

Figure 8. Comparative intensity development of C III at 464.74 nm

1. Energy Dependency of Plasma Behavior

In Fig. 9, an exemplary spectrum at the highest energy level of 47 J is provided where all the observed species are marked. It can be noted that argon, oxygen and nitrogen species have been observed which is an experimental confirmation for the thus far theoretical concept of air-breathing propulsion. To exemplify the behavior of the different species with increasing energy levels, the measured number of oxygen lines in their various excitation levels have been plotted in Fig. 10. The oxygen exemplifies the overall behavior for the discovered species of argon, nitrogen and copper in that the number of lines and their excitation levels increase with an increased energy level.

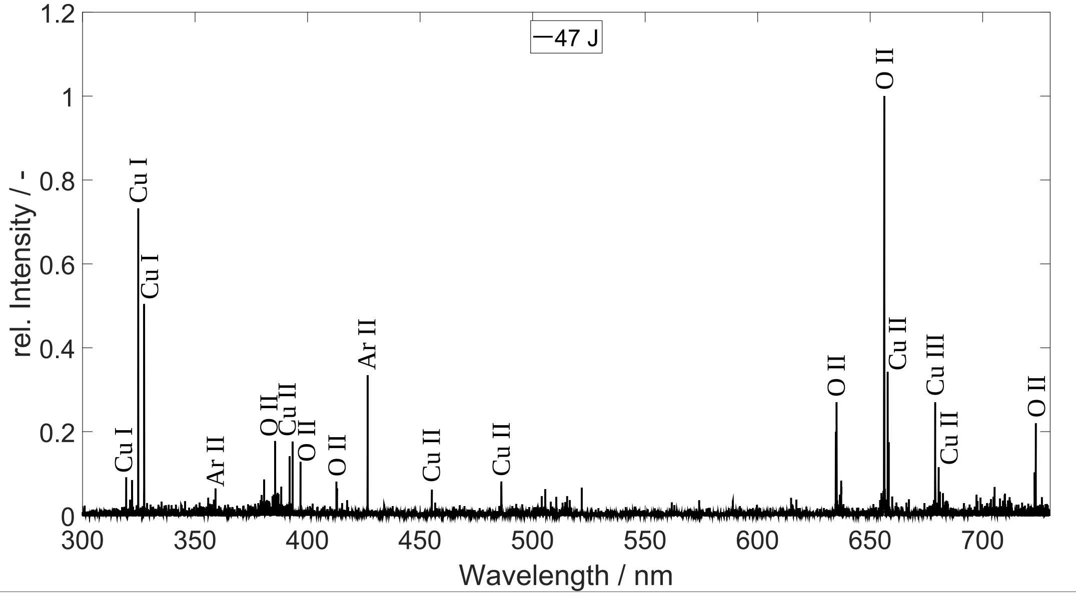

Figure 9. Species and normalized intensities of air-breathing PPT at 7500 Pa and 47 J

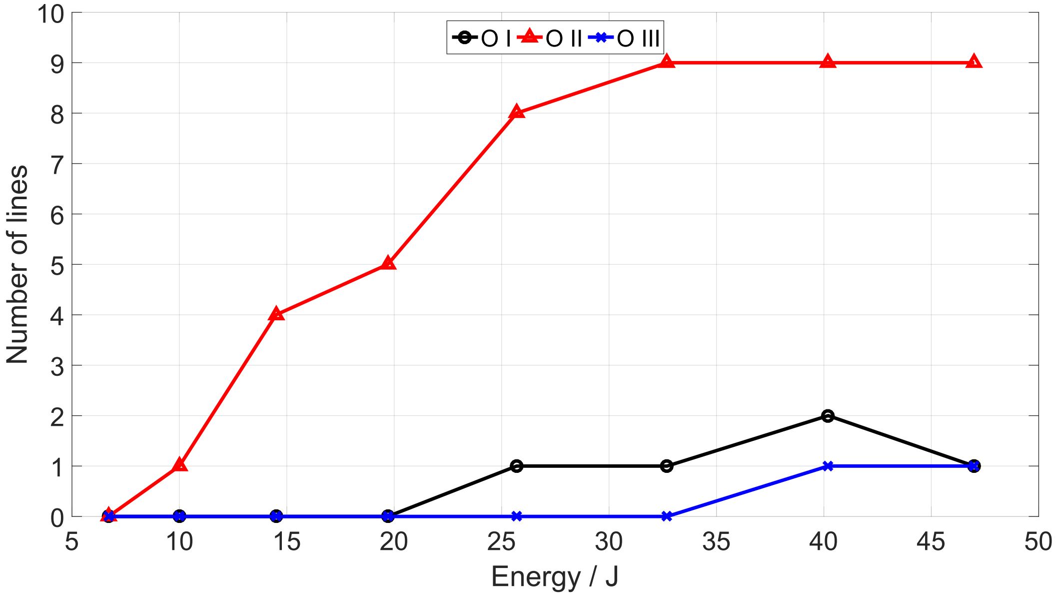

Figure 10. Number of detected oxygen lines in each excitation state

2. Pressure Dependency of Plasma Behavior

Since the same general species as in the energy dependency investigation were observed, a repeated display of a whole spectrum is omitted and the species' individual behavior is discussed. The pressure behavior of the PPT's plasma is exemplified with the data obtained for the present argon species, since those yielded the most processable information for further analysis. In Fig. 11 the number of detected Argon species is displayed.

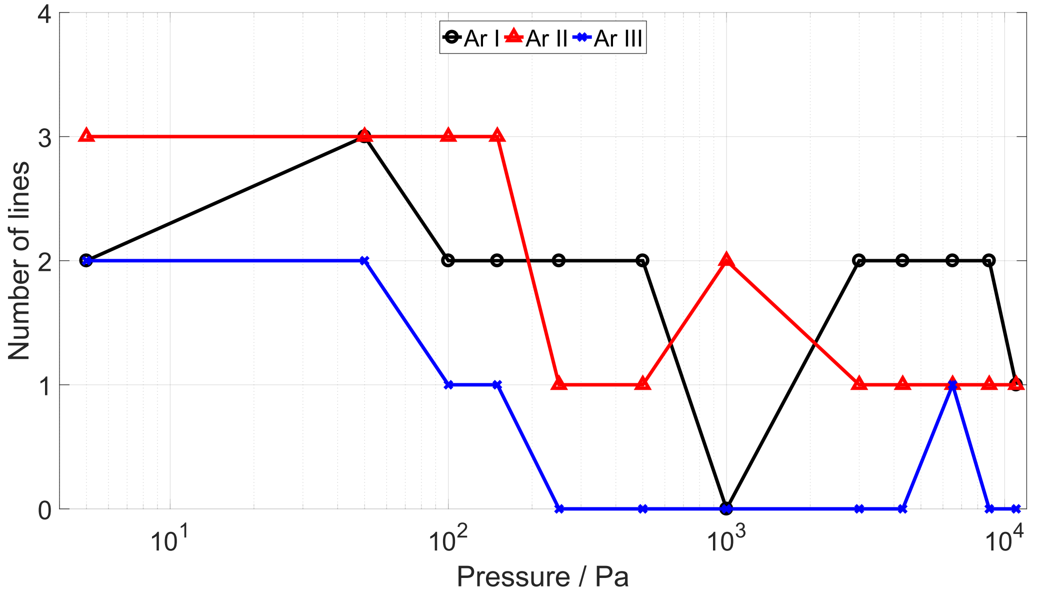

Figure 11. Number of detected argon lines in each excitation state

The discovered argon lines show a clear tendency to increase towards lower pressures in terms of the number of detected lines and ionization level. This holds also true for the intensity development of the more highly ionized argon lines, which still have a positive gradient at the lowest measured pressure. This indicates that even lower pressures might yield an even higher propellant utilization efficiency for argon. To further investigate this behavior and possible indication for a high propellant utilization, the electron temperature for argon was calculated using Boltzmann plots, which under the assumption of an LTE is equal to the excitation temperature. The results of this calculation for the pressure range in which a high enough number of lines for a Boltzmann plot were observed are plotted in Fig. 12.

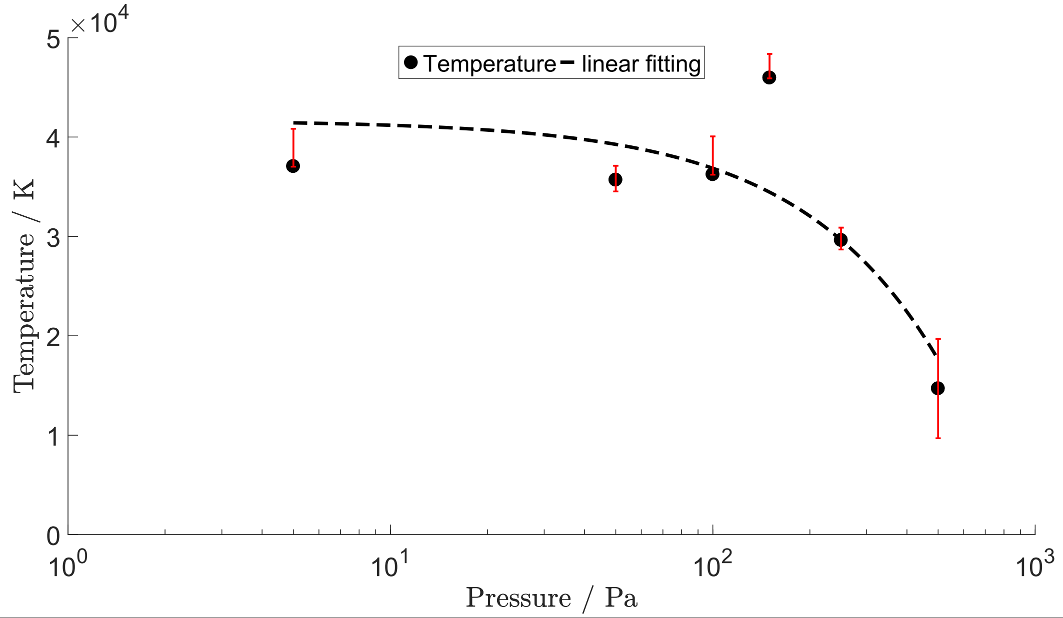

Figure 12. Temperature development argon

In alignment with the thus far observed phenomena, the derived excitation temperatures for argon increase linearly with decreasing pressure which indicates an increased energy coupling into the plasma at lower pressures.

Taking these points into consideration, the investigation of the plasma plume's pressure dependency has indicated that propellant utilization efficiency and thus the thruster's efficiency can be steadily increased with decreasing the injection pressure. In part I of this study[8], an increased contribution of the accelerated plasma to the thruster's impulse bit has been observed, which further confirms the conclusions drawn from the obtained data in this study. It must however be noted that since this study has already applied pressures as low as 5 Pa and the improvement appears to be linear, there is not much room left for improvement by reducing the pressure.

3. Evaluation of Plasma Plume Symmetry

To judge the symmetry of the plasma plume, the achieved intensity values of the discovered lines have been compared using equation (1). Thereby a resulting value of 0 would indicate an equal value at the different positions.

$$I_{rel} = \frac{I_{Middle} - I_{Top/Bottom}}{I_{Middle}} \tag{1}$$

For the various lines used for this evaluation, values between 1 and -2.5, indicating significant positive and negative diversions from the values at the thruster's center-line, have been calculated. Moreover, no recurring pattern could be distinguished, all lines showed different, random appearing patterns when the values calculated were plotted over the different pressure levels. As of the results of this investigation, there appears to be no symmetry in the plasma plume, which requires further research and possible improvement of the used thruster.

IV. Conclusion

The parallel-plate PPT with PTFE and PFPE as a propellant and the coaxial PPT Asuka utilizing dry air were successfully operated and reliable measurements with an optical emission spectrometer could be achieved.

Comparing the behavior of the solid PTFE and the liquid PFPE propellant at different discharge energies in the parallel plate PPT, it was discovered that both propellants behave quite similarly. This holds true for the type and ionization level of the observed species as well as the comparative number of ionized particles. Small differences in the ionization behavior at higher energy levels between the two propellants could be observed. The liquid PFPE shows a trend towards higher ionized species compared to the solid PTFE. This has to be considered together with the fact that the PFPE's mass bit is significantly higher than the PTFE's, which indicates a low propellant utilization efficiency for PFPE.

In the spectroscopic measurements of the air-breathing coaxial PPT Asuka the air species oxygen, argon and nitrogen were observed and an experimental validation of the air-breathing concept was achieved. With increasing discharge energies the number of discovered lines of air species in the plasma as well as their ionization levels increased, which indicates a higher propellant utilization efficiency at higher energy levels. The same tendency could be observed with decreasing pressure levels and was further reinforced by a calculation of the excitation temperatures within the plasma under assumption of an LTE.

With this work the general functionality of air-breathing propulsion has been confirmed and various parameter dependencies have been discovered. The results recommend further research into this field to determine an optimal operation point and enable a fact-based evaluation of the feasibility of such a system on a satellite.

Acknowledgments

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