Experimental Investigation of the LES 8/9 Pulsed Plasma Thruster Plume

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Abstract

A plasma diagnostics package and related data processing techniques were developed at NASA Lewis in order to characterize the plume of a LES 8/9 Pulsed Plasma Thruster. The setup included single Langmuir probes, and fast ionization gauges mounted on a rotating rake mechanism and a residual gas analyzer. Instrument calibration was also performed. Single Langmuir probe results show that the plasmoid produced during the pulse contains two waves with an average ion velocity of 60 km/s and 30 km/s, respectively. Fast ionization gauge data show that the neutrals in the plume travel with much lower speeds than the ions. Based on the residual gas analyzer data, the plume is found to be composed primarily of C, F, CF, CF\textsubscript{2}, and CF\textsubscript{3}.

Introduction

In recent years, pulsed plasma thrusters, or PPTs, have become the recipient of much interest in the satellite community. The thruster’s light weight, low cost, ease of operation, and reliability have all contributed to its appeal. Currently the thruster is being considered, or has been chosen, as the on-board propulsion system for several missions in the near future\cite{1}. The long term goals of this project are to develop diagnostics and use them to characterize the plume of the PPT. These experimental studies are in concert with efforts aimed at developing an advanced PPT plume model\cite{2,3}. Knowledge of the plume composition and transport will help satellite designers eliminate possible interactions between the spacecraft and the plume.

Pulsed plasma thrusters, such as the one used in this project, are a type of electromagnetic electric propulsion system. The thrusters have been in development since the 1950s, and have been successfully flown\cite{4}. PPTs use solid Teflon as the propellant which is spring fed to a pair of electrodes, in a rail configuration. One of the electrodes also has an igniter plug, located at the face of the Teflon bar, as illustrated in Figure 1. In a single pulse, the following events occur. First, charge is built up in the capacitor. The spark plug then fires, ablating and ionizing enough plasma to allow a current to flow between the two electrodes. This main discharge ablates and ionizes more Teflon, and also creates a magnetic field between the electrodes. The interaction between this magnetic field and the charged particles in the plasma, the $\mathbf{J} \times \mathbf{B}$ interaction known as the Lorentz force, accelerates the plasma, producing thrust. The plasma produced by the
thruster exits the nozzle in the form of a highly concentrated blob. Various studies, using a range of thrusters, have been undertaken to characterize the exhaust plume of the PPT. Studies of the LES 6 PPT, flown in 1968, show centerline ion velocities between 25 and 42 km/s with an average of 27.9 km/s and energetic neutral velocities between 4 and 18 km/s. These velocities depended on the degree of ionization of the particle, as triply ionized exhaust particles were found to travel over twice as fast as singly ionized particles. Based on thrust stand measurements, the average exhaust velocity was estimated at approximately 3000 m/s. The LES 8/9 flight qualified PPT has ion exit centerline velocities of up to 40 km/sec with an average plasma velocity of 10 km/sec. Recently, Myers et al. confirmed previous findings that the plume is primarily confined to a 40 degree half angle when it exits the nozzle. Another important characteristic of the plume is that it is not symmetric. Instead, it is wide in the plane parallel to the electrodes and narrow in the perpendicular plane.

The composition of the PPT plume is of special interest to the determination of the contamination potential to spacecraft surfaces. Hirata and Murakami, using the Japanese ETS-IV PPT, found that the plume consists of C, F, CF, CF₂, and CF₃ molecules, and that the majority of the plume consisted of CF molecules. The average molecular weight of the exhaust was calculated by examining the mass flow rates of the thruster and the vacuum chamber pumps. They used a mass spectrometer to analyze the residual gas in the plume, although without considering the different sensitivities that each gas might have with the mass spectrometer. A spectroscopic study of the plasma inside the nozzle of the LES 6 PPT found neutral, singly ionized, doubly ionized and triply ionized Carbon and Fluorine, and small amounts of iron, most likely from the steel electrodes. Mass deposition studies using the LES 8/9 have found no measurable deposition upstream of the thruster exit after 2x10⁵ pulses. Optical transmittance measurements of collimated quartz samples located in the backflow region showed no change as well.

The objectives of this study were to take ion velocity, pressure and composition measurements of the exhaust plume of a LES 8/9 PPT. From the pressure measurements, neutral density can be calculated. Previous plume characterization studies have been somewhat hampered by the size of the test facility used. This study used a larger vacuum tank, in order to reduce the interference caused by wall reflections. The data collected in these experiments can benefit the plume modeling effort, providing boundary conditions and verification of the code.

Experimental Apparatus

Pulsed Plasma Thruster

The thruster used in our experiments is a Lincoln [Laboratory] Experimental Satellite 8/9 (LES 8/9) Pulsed Plasma Thruster. Each of the two thruster nozzles uses a piece of Teflon that was originally 26.7 cm long and 2.3 cm square, dimensions that provide approximately 9.4 million thruster pulses. The capacitor used to store the energy for the discharge is oil filled, has a capacitance of 17 µF, and is capable of 10¹¹ firings. It is charged to 1538 volts for every firing, and the discharge results in a peak current of 18,000 A in the plasma. On average, every pulse ablates 28.5 µg of Teflon and has a duration of 12 µsec. The LES 8/9 has a canted exit channel, and these experiments used the nozzle extension described in Myers et al. to make the nozzle symmetric.

Diagnostics

All tests were carried out at NASA LcRC Electric Propulsion Laboratory. The PPT was mounted on a support arm at the top of a 3 meter tall, 1.5 meter diameter vacuum tank using the test stand designed by Myers et al. The tank was cryopumped to a base pressure of ~ 1 x 10⁻⁷ Torr, and the time averaged pressure during thruster firing was ~ 6x10⁻⁶ Torr. A movable, computer controlled probe rake was built that would allow many readings to be taken in the vacuum tank without repressurizing and repositioning the probes. The rake is designed so that the gauges and the nozzle of the thruster are collinear, allowing time of flight measurements to be taken. It can swing through 90 degrees, from a vertical position directly underneath the nozzle to a horizontal position. A schematic of the probe rake mounted in the tank is illustrated in Figure 2.
Ion Velocity Measurements

Single Langmuir probes were used to measure ion velocities in the PPT plume. The probe tip was made of .1625 cm copper wire and a negative bias of 40 Volts was used, in order to collect ions. In previous studies using small bell jars, the entire jar was effectively in contact with the plasma, and thus the ground could simply be connected to the jar. In larger facilities, such as Tank 13 used in our study, the tank does not provide a suitable ground. Therefore the circuit was grounded to the plate supporting the probe. The single Langmuir probes were placed on the probe rake, at 0.3m and 0.45m from the nozzle exit. During testing, the rake was positioned at 90, 60, 40, 20, and 0 degrees from the centerline of the thruster, in the plane perpendicular to the electrodes in the thruster. At each position, 5 pulses were recorded with the single Langmuir probes, with each pulse consisting of two traces, one from each probe.

Pressure Measurements

Fast Ionization Gauges (FIGs) were used to measure the gas pressure in the PPT plume. FIGs calculate pressure by measuring a pressure dependent characteristic of the gas. A FIG with a response risetime of 3 μsec and a useful pressure range of $10^{-8}$ to $10^{-2}$ Torr was used in the experiment.

The pressure can be calculated from the fast ionization gauge by using the formula

$$P = \frac{V}{S + I} \quad \text{[Eq. 1]}$$

where $I$ is the current supplied to the filament (in mA), $V$ is the voltage output from the gauge, and $S$ is the sensitivity factor (in Volt Torr$^{-1}$ mA$^{-1}$). The sensitivity factor is dependent on many physical factors, including the distances between the components of the gauge head and the circuitry used to control the gauge and the gas that the gauge is measuring.

The FIG was calibrated in a bell-jar facility using nitrogen gas. The objective of the calibration was to determine the sensitivity of the gauge over a range of pressures and filament currents. A spinning rotor gauge was used for reference. Sample results from this calibration are shown in Figure 3.

In order to use the fast ionization gauges in the PPT plume, the relative sensitivity of the gauge to the constituents of the PPT plume must be established. Hirata and Murakami found C, F, CF, CF$_2$, and CF$_3$ molecules in the PPT plume. Each component of this mixture presumably has its own relative sensitivity, which must be combined to provide a single relative sensitivity for the plume. The relative sensitivity for each of these molecules has not been measured. Hirata and Murakami found that the average molecular weight of the plume was 31 g/mole, equal to that of a CF molecule. Furthermore, it was found that there was about three times as much CF as C, F, CF, or CF$_3$. It is reasonable, then, to assume that CF, and thus its relative sensitivity, dominates the plume of the PPT. If known relative sensitivities are plotted versus the number of electrons in the molecule normalized to nitrogen, a nearly linear plot can be derived as shown in Figure 4. Using this plot and taking a weighted average based on plume composition, the relative sensitivity of the plume is found to be 1.12.

The FIG was attached to the probe rake at .30m from the nozzle exit plane. It was clear from the data collected by the gauge that the various charged particles in the plume were saturating the gauge. In an attempt to prevent charged particles from affecting measurements, the gauge head was wrapped in copper screen and biased negatively in order to prevent the electrons in the plume from entering the gauge. Pressure readings were taken at 40, 50, 60, 80 and 90 degrees from the thruster centerline in the plane perpendicular to the electrodes, as shown in Figure 2. Two pulses were recorded for each position.

Plume Composition

In an attempt to better quantify the PPT plume composition, a residual gas analyzer (RGA) was used. This instrument measures the ratio of mass-to-electric charge in a molecule by ionizing it then passing it through a mass filter. The theory of operation is very similar to the fast ionization gauge, except in this case only ions of one mass reach the collecting wire at a time. By varying the masses that are filtered, the molecules present in the gas being analyzed can be found. The RGA used in this experiment can detect molecules with masses from 1 to 200 AMU, with a resolution of 1 AMU. The analyzer head was attached
to the side of the vacuum facility, and was mounted on a flange at the bottom of the vacuum tank, about 2 meters from the thruster.

Results and Discussion

Ion Velocity

The velocity of the ions in the pulsed plasma thruster plume can be calculated using the data gathered by the single Langmuir probes. To do this, the trace from the near and far probe are compared for a single pulse. Typical traces are shown in Fig. 5. The velocity can be calculated using the simple formula

\[ V = \frac{D}{T_f} \]  

where \( D = 0.15m \), the distance between the probes and \( T_f \) is the difference in time between the peaks on the graph.

Single Langmuir probe data was collected at 0, 20, 40, 60, and 90 degrees from the centerline of the PPT nozzle, in the plane perpendicular to the thruster's electrodes. Five pulses were recorded at each position, and the ion velocity was calculated for each pulse. As the traces from the probes were examined, one prominent characteristic was discovered. Almost without exception, each probe trace showed two velocity peaks, an initial large peak followed by a smaller peak. Sample traces can be seen in Figure 5. This indicates the presence of two waves of ions in the thruster's exhaust and manifested itself across all angles as well. In an effort to understand the readings better, velocity measurements were taken for both peaks. From this analysis, it seems that the second peak provides velocity results that agree with those found previously for the LES 8/9 thruster. Velocity plots for the first and second ion waves are shown in Figures 6 and 7.

The plots show that along the centerline, the first peak, or wave of ions, has a velocity almost twice that of the second peak. Both peaks show the drop in plume intensity at 40 degrees that had been previously noted in earlier studies. There is an increase in the first wave velocity at 60 degrees. It is important to note that this peak is not seen on the second wave velocity data. As Figure 7 shows, the velocities of the second wave decrease with increasing radial distance off the plume centerline.

There are several possible explanations for the dual population of ions. Thomassen and Vondra found that faster moving multiply ionized ions are produced during the early stages of the PPT pulse. The slower ions could also be attributed to the slug-restrike-steady state PPT mode of operation outlined by Turchi.

The errors in the velocity calculations are due to errors in position (+/- 1 cm) and time. Errors in time are due to the uncertainty involved in picking the peak of the wave from the single Langmuir probe trace. This was estimated to be +/- 0.05x10^{-3} seconds, which is about the width of an average peak. Total estimated error in the velocity measurements is +/- 16.6%.

Pressure Analysis

Late time pressure measurements are shown in Figure 8. This plot shows pressure change over time as a function of angle from centerline, 0.30 meters downstream from the nozzle exit. These pressure measurements are taken after the FIG saturation passed, indicating the presence of slow neutral particles in the plume of the PPT. Figures 10 and 11 show a FIG and Single Langmuir probe output for the same pulse. From this plot, it is clear that the bulk of the fast moving ions in the plume have passed, and that the FIG is measuring pressure due to neutral particles and ions. Figure 11 shows a detail of the FIG and SLP's reaction to the passage of the ionized core of the plasma pulse.

An estimate of neutral particle velocity can be made as well. If it is assumed that all neutral particles are released at the start of the pulse, it is seen that the neutral particles travel between 100 and 1000 m/s. The value could be more accurately estimated if multiple FIGs were used.

From the pressure it is possible to calculate the neutral densities, using the equation

\[ P = nkT \]  

where \( k \) is the Boltzmann constant, \( T \) is the temperature of the particles in Kelvin, and \( n \) is the number density. To calculate the neutral particle density, the temperature of the neutral gas must be known. Under the assumption that the neutral gas has not cooled during the expansion, we can use the temperature of the Teflon's surface in Equation 3. A study of Teflon
temperature during thruster operation done at NASA Lewis found that after about 11,000 pulses of a PPT, the Teflon face reached a temperature of approximately 420 K. Figure 9 shows neutral number density for different times as a function of angle. Time in this plot starts at approximately 0.75 msec after the beginning of the pulse, since measurements could not be taken sooner due to the gauge saturation.

It would be very difficult to quantify the uncertainty in these measurements, since many interdependent factors, such as gauge sensitivity, relative sensitivity, and plume composition, come into play. Further experiments should be conducted to verify these results.

**Plume Composition**

An RGA output of the PPT plume taken in Tank 13 is shown in Figure 12. There are three obvious main peaks on the RGA trace, at 31, 50 and 69 AMU. These correspond to CF, CF₂, and CF₃, respectively. A peak at 12 AMU is also shown in Figure 12, indicating carbon. The smaller peaks at 16 and 18 are due mainly to air, however fluorine has an atomic mass of 19 and is potentially being detected here as well. If aluminum from the thruster body and exhaust channel were present, it would show as a peak at 27 which would be hard to distinguish from the N₂ at 28 AMU. The small peak at 44 is due to background CO₂. It is also likely that the peak near 63 AMU is due to copper eroded from the thruster’s electrodes. Additionally, the peak near 88 AMU may be due to CF₄. The other peaks above about 70 AMU may be molecules eroded from the composite nozzle extension, or from impurities in the Teflon. It is unlikely that they result from pump oils since they do not appear in traces taken in the tank when the thruster was shut off, although this is a possibility to be investigated.

The RGA traces show that the plume consists primarily of CF, CF₂, and CF₃ molecules and this agrees with previous studies. No conclusion should be drawn from the relative heights between these three constituents in the RGA readout. Since the RGA was placed on the differential pump during calibration, it was impossible to determine the pressure of the gas being sampled and thus to calibrate the RGA’s sensitivity.

The accuracy of an RGA such as the one used in this analysis of the PPT plume is tenuous at best. In an ideal situation, the analyzer should be placed directly in the exhaust plume of the PPT, and should have a sampling rate fast enough to sample at least one AMU as the plume passes by the analyzer head. In the current setup, the thruster is fired over a period of time, leaving a background gas in the tank consisting of various molecules. These molecules might not be the ones in the PPT plume, since they have had time to bounce around and react with other molecules in the tank. A single, 200 AMU RGA trace takes many seconds, and it is impossible to say that it is giving an accurate analysis of the contents of the plume. The constituents found above might not be those that exist in the core of the plume soon after the thruster fires.

**Conclusions**

From the single Langmuir probe data, it was found that there are two waves of ions in the PPT plume. The dual wave nature of the ions may be attributed to ion production and acceleration mechanisms in the PPT. These issues should be further investigated through experiments and PPT modeling.

Useful insights about neutrals in the PPT plume can be drawn from the limited amount of data collected from the fast ionization gauges. Neutrals flow well after the passage of fast ions. Unsaturated FIG data were collected starting at 0.75 ms after the pulse, lasting up to 2.0 ms after the pulse. Undoubtedly, the maximum pressure and density in this region is much higher than the values shown here, but this data should provide a reference, especially in an unsteady plume model.

Using a residual gas analyzer, the presence of C, CF, CF₂, and CF₃ in the plume was confirmed. Trace amounts of thruster body materials were detected as well. Because the RGA samples the gas in the vacuum chamber over time, care should be taken when using this data in any modeling efforts, as the samples taken may not be the constituents in the core of the plume.
References


14 Kamhawi, H., Ohio State University, Personal Communication, September 18, 1996.

![Figure 1: Schematic of pulsed plasma thruster](image)

![Figure 2: Probe rake mounted under PPT, showing probe positions and rotation angles](image)
Figure 3: Sample FIG calibration curve in Nitrogen

Figure 4: Relative sensitivities vs. number of electrons/molecule [Flaim and Ownby, 1971]

a) Centerline reading  
Figure 5: Sample SLP traces at 0 and 40 degrees from thruster centerline

b) 40 degrees off centerline

Figure 6: Velocity of first ion wave

Figure 7: Velocity of second ion wave
Figure 8: Pressure change over time as a function of angle from centerline

Figure 9: Neutral density change over time as a function of angle from centerline

Figure 10: Simultaneous FIG and SLP traces

Figure 11: Expanded view of FIG and SLP during saturation

Figure 12: RGA trace of vacuum chamber after thruster pulses