

Performance Measurements of Electric Solid Propellant in an Ablative Pulsed Electric Thruster

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Electric solid propellants are advanced solid chemical rocket propellants that can be controlled (ignited, throttled and extinguished) through the application and removal of an electric current. These propellants may also be used for electric in-space propulsion, specifically in the ablative pulsed plasma thruster. In this paper, we will investigate the performance of an electric solid propellant operating in an ablation-fed pulsed plasma device by use of an inverted pendulum micro-Newton thrust stand. Namely, the impulse-per-pulse and the specific impulse of the device using the electric solid propellant will be reported for test runs of 100 pulses and energy levels of 5, 10, 15 and 20 J. Further, the device will also be tested using the current state-of-the-art pulsed plasma thruster propellant, polytetrafluoroethylene. The performance of each propellant will be compared for each energy level using an identical setup and apparatus. This comparison of performance between propellants in a controlled setting will allow for better understanding of previous experimental observations.

I. Introduction

Recent innovations in the solid rocket propellant field have led to the development of a solid propellant that is safe, throttleable, and green with at-will on-off capability. These electric solid propellants (ESP's) ignite and decompose when electric power is applied at sufficient current and voltage¹. This decomposition is a highly exothermic process that generates hot gas at a burn rate that can be throttled by varying the applied current. Removal of the voltage and current extinguishes the reaction, which may be restarted by reapplication of electric power. Because this reaction is only induced by electric current, ESPs are not susceptible to accidental ignition by spark, impact or open flame. These characteristics are extremely beneficial compared to traditional solid rocket propellants which are not throttleable, toggleable, or insensitive to external ignition. The advent of ESPs expands the potential applications for solid propellants that were previously infeasible.

Development of ESPs began in the 1990's with the design of an automobile air bag inflator propellant (ABIP) using materials safe for unprotected human contact (i.e. "green" materials). This ABIP was ammonium nitrate-based and was later repurposed for use in other areas, including rocket propulsion. Shortly thereafter, "ASPEN," the first digitally controlled extinguishable solid propellant, was developed. This propellant featured additives with the ammonium nitrate base to lower melting point and increase electrical conductivity². This material exhibited performance metrics comparable to that of previous solid rocket propellants, but major problems existed with the repeatability of ignition. Further development led to an advanced formula with higher specific impulse and conductivity. The result was a high performance electric propellant, or HIPEP¹. In this solid energetic material, the ionic liquid oxidizer hydroxyl-ammonium nitrate (HAN) exhibits pyroelectric behavior unique to energetics. When

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electric power is applied, the proton transfer reaction between hydroxyl-ammonium and nitrate is promoted, and the level of nitric acid rapidly rises in the material eventually triggering ignition of the propellant. This behavior may facilitate a dual-mode propulsion system wherein a high thrust chemical mode using direct current to incite pyroelectric gas generation is paired with a high specific impulse (I_{sp}) electric mode. One promising electric-mode configuration is a pulsed electric propulsion device known as the ablation-fed pulsed plasma thruster (APPT). The ammonium nitrate-based ABIP was previously tested in Aerojet's modular test unit (MTU) and reported impulse bits were roughly 50-80% of the polytetrafluoroethylene (PTFE) solid propellant typically used in this unit¹.

Pulsed plasma thrusters³ (PPTs) have been in use since the first orbital flight of an electric propulsion device in 1968. PPTs offer repeatable impulse bits with higher exhaust velocities than can be achieved using chemical thrusters. Ablating PTFE in the discharge to yield a working fluid, APPT's have the added benefit of inert propellant storage with no pressure vessel requirements. PPT's are typically used to fulfill secondary propulsion needs on spacecraft such as station-keeping⁴⁻⁷ and attitude control⁸⁻¹⁰. Broadly, PPT's may be classified as either rectangular or coaxial geometry³. Coaxial APPT's, like that of the PPT-4¹¹, begin with a central and a downstream electrode and often have a conical-shape dielectric between the electrodes. The central or upstream electrode is typically cylindrical while the downstream electrode is ring-shaped, and either may be used as the positively charged electrode (anode). Solid propellant fills the space between electrodes and may be fed from the side through breeches in the conical dielectric. Most commonly this solid propellant is the inert polymer, PTFE, which is held as the state-of-the-art for APPTs. A capacitor or bank of capacitors is charged to a few kilovolts, with that voltage applied across the electrodes. The main arc discharge is initiated by an ignitor, which is similar to an automotive spark plug but is usually smaller and custom-designed and is always located in or near the cathode in a PPT. This arc discharge is fueled by ablation from the surface of the solid propellant, with the discharge feeding heat into the propellant to ablate it. The coaxial PPT is a device dominated by electrothermal acceleration mechanisms, with the energy of the arc heating the gas to yield high exit velocities through gas-dynamic acceleration. Ablation processes are at the core of APPT operation, and thus many studies on the ablation of PTFE exist in literature¹²⁻¹⁵.

Our recent work has compared the ESP HIPEP with traditional PTFE in a PPT test article¹⁶⁻¹⁸. At high temperatures and over long (~ms) time-scales, it is known that HIPEP undergoes a thermal decomposition process, while PTFE evaporates after depolymerization. However, ablation processes present in APPTs occur on much shorter timescales, as the discharge current has a period of less than 10 μ s. LCR circuit model analysis has shown that the conductivity of the HIPEP material does not affect the discharge current significantly. The specific ablation of HIPEP is roughly twice that of PTFE, but on the same order of magnitude. This difference in ablation mass between the two propellants can be directly attributed to differences in the material thermal and chemical properties¹⁶. Plume measurements of these same HIPEP microthrusters indicate electron temperatures (1-2 eV) and densities (10^{11} - 10^{14} cm⁻³) of the weakly ionized plasma comparable to that of PTFE fueled APPTs. Exhaust velocity measurements indicate similar performance of HIPEP relative to PTFE in the microthrusters. Further, it has been shown that the fraction of late-time ablation mass is similar between propellants. Estimates from high-speed imagery from a pulsed HIPEP microthruster suggest that up to 50% of the mass ablated may be attributed to low-speed macroparticles ejected after the main current pulse¹⁷.

The objective of this work is to investigate the performance of the HAN-based HIPEP material relative to that of PTFE in an ablative pulsed plasma device. Namely, the impulse and specific impulse of the device will be measured using an inverted pendulum thrust stand. The device is a pulsed electric apparatus closely resembling a coaxial APPT and designed to permit quantification of the propellant specific ablation and was used with both PTFE and HIPEP. For each propellant, the device was operated for 100 pulses in vacuum, with the impulse-per-pulse and the total propellant mass loss recorded over the test run. These measurements are the first reported one-to-one performance comparisons between the HIPEP and PTFE materials in an ablative pulsed plasma device. By measuring these quantities, some light may be shed on how the previous observations of the HIPEP material affect performance and will guide future design of pulsed electric devices using this propellant.

II. Experimental Methods

A. High Performance Electric Propellant

The ESP is a HAN-based solution solid manufactured by Digital Solid State Propulsion (DSSP) using "green" ingredients and processes free of harmful fumes. HIPEP has a chemical composition of 75% HAN oxidizer (an inorganic ionic liquid), 20% polyvinyl alcohol (PVA) fuel binder, and 5% ammonium nitrate¹⁸. It is mixed in standard chemical glassware, with only gloves and safety glasses needed for protection, and cured at room temperature (35°C/95°F). The mixed liquid is then poured into a mold, curing to form a soft solid with the appearance and texture of a soft pencil eraser. In a typical PPT, the PTFE is an electrical insulator between the electrodes. The conductivity

of the ESP in this work is comparable to “highly conductive” ionic liquids (e.g. 1-2 S/m). Previous work has shown that the conductivity of the HIPEP has a negligible effect on the measured current in the arc discharge. Further, it has been observed that the HIPEP material ablates more readily than PTFE in an ablation-fed arc, which may be attributed to thermodynamic properties of the solid propellant. It is currently unclear how the additional ablation mass contributes to the thrusting performance of the material in an ablation-fed thruster.

B. Electric Propellant Thruster Experiment

A coaxial geometry pulsed plasma device was used for the ablation mass study. Figure 1 details the geometry of the arc-discharge chamber. It should be noted that this was designed primarily to study the mass ablation of solid PPT propellants and not as a high-performance thruster. A circular stainless steel rod serves as the anode (positive) and a stainless steel plate with a circular hole serves as the cathode (ground). The assembly is housed in a nonconductive PEEK body. The propellant tube (HIPEP or PTFE) sample has length 12 mm and inner diameter 6.35 mm. Because HIPEP is conductive, the propellant is isolated electrically from the two electrodes by thin PTFE washers with inner diameter ~7 mm. These washers have an approximate thickness of ~0.5 mm which is sufficient to hold off the maximum voltage (2.23 kV) used in the present work. The washers remain during PTFE testing to keep electrode spacing consistent between propellant samples.

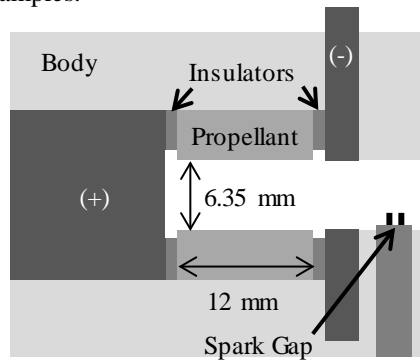


Figure 1: Diagram of the coaxial pulsed plasma test article.

The test article and the capacitor bank are co-located inside the vacuum test facility. It is intended that the arc discharge occurs in the cylindrical cavity formed by the inner propellant tube wall and the anode end, with current flowing between the anode and cathode. Because the test article is at vacuum, the capacitor can be charged to a large voltage (1-5 kV) across the anode/cathode-gap without initiating a Paschen breakdown. Breakdown of the gas is initiated by a small spark gap constructed of two tungsten wires cemented in a two-bore alumina tube with ~2 mm exposed tip lengths. The wire tips are in the exhaust channel just downstream of the cathode as shown in Figure 1. A capacitor discharge ignition (CDI) circuit creates a low energy spark across the tungsten wire tips, introducing several electrons into the cylindrical cavity of propellant. These charge carriers allow the flow of current to begin between the electrodes, seeding the main arc discharge.

C. Compact Thrust Stand

This work was conducted in Electric Propulsion Facility 1 at the University of Illinois Electric Propulsion Lab. This vacuum facility is approximately 1000 L in volume and achieves a base pressure of $\sim 2 \times 10^{-5}$ torr. Housed in this facility is the UIUC Compact Thrust Stand designed for accurate measurement of thrust and impulse bit in the micro- and milli-Newton range¹⁹. This stand is of an inverted-pendulum design with a footprint of merely 55 cm and 50 kg thruster mass capacity. Two modes of stand operation allow for constant thrust force measurement in the range of 1-10 mN and impulse measurement in the range of 0.1-3 mN-s. In this work, the stand is operated in impulsive measurement mode to determine the impulse-per-pulse, or impulse bit, of a pulsed plasma device. Calibration in this mode is performed using a remotely actuated impact hammer to deliver an impulse of typically 100-1000 $\mu\text{N-s}$ to the stand. This calibration impulse is delivered directly to a piezo-electric force transducer, which measures the force imparted as a function of time. Integration of this signal yields the impulse imparted to the stand. Each strike of the hammer generates a deflection of the thrust stand which is measured by a linear variable differential transformer (LVDT). The integrated force signals and associated maximum stand deflection measurements are then combined to establish a calibration curve of stand deflection vs. known impulse.

III. Future Work

The Electric Propellant Thruster Experiment will be operated in the facility described using both PTFE and HIPEP as propellant. Using the compact thrust stand, the impulse bit and specific impulse of each propellant will be reported for the energy range of 5-20 J and compared. This investigation will allow for further conclusions to be drawn from the previously observed behavior of these materials in the ablation-fed device. Though the device used in this work is not a thruster design optimized for performance, these results may help drive future innovation.

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