Gas-Fed Pulsed Plasma Thrusters: Experiment, Diagnosis, and Modeling

Andrew Mackowski

Performed under the guidance of
Professor Edgar Choueiri and Jimmy Cooley

September 11, 2006

Abstract

This report details my summer activities in the Electric Propulsion Laboratory at Princeton University. I worked with a type of thruster designed for spacecraft propulsion that uses electromagnetic effects to accelerate its propellant. During my stay at the lab, I conducted experimental work (firing the thruster and taking data), developed a diagnostic tool, and modeled a component of a new thruster idea (a heated filament). These activities have given me a taste of how scientific research is conducted and sparked my interest in computational simulations. I have left behind a useful tool that can be used to analyze past and future experiments, and helped shed light on problems facing filament thrusters.

1 Introduction

In the field of spacecraft propulsion, propellant weight is one of the biggest obstacles, forcing spacecraft in orbit to carry large amounts of chemical fuel. The expense of launching this fuel with the spacecraft has motivated the design of other methods of propulsion that require minimal fuel. One such thruster is a gas-fed pulsed plasma thruster (GfPPT). This device works by ionizing an inert gas, running a current through it, and using the resulting electromagnetic forces to accelerate the gas particles and produce thrust. Although it produces less thrust than a chemical rocket, this electric thruster uses its fuel much more efficiently (in other words, it can achieve a higher specific impulse). In addition, the GfPPT is pulsed, allowing precise throttling and enabling its use on smaller spacecraft with limited steady-state power.

A schematic of a GfPPT is shown in Figure 1a. The first part of an operating cycle is when propellant gas is injected into the thruster cavity. At the same time, a voltage difference is applied across the anode and cathode. The electric field between the anode and cathode, combined with an electron source (such as spark plugs), effects gas breakdown. Now that the gas is ionized, a large

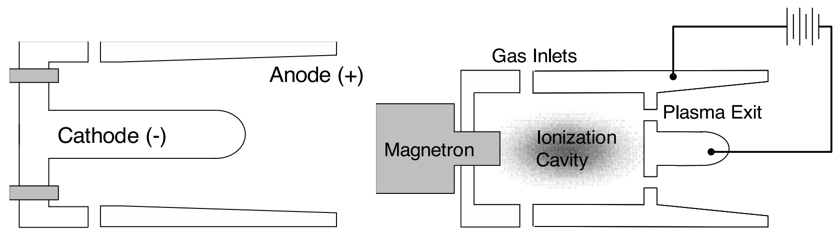

Figure 1: (a) A typical gas-fed pulsed plasma thruster (electron source not shown). (b) Schematic of a microwave-initiated pulsed plasma thruster.

current arcs through it between the anode and cathode. This arc takes the form of a current sheet, which is propelled down the thruster tube by its own electromagnetic forces. Thrust is created as the current sheet accelerates and sweeps the fuel with it.

2 Experiment: Microwave GfPPT

One problem facing GfPPT's is the uniformity of the current sheets they produce. For example, when spark plugs are used to initiate gas breakdown, the current sheet may become localized near the greatest spark. When a current sheet doesn't uniformly fill the thruster tube, it is not able to push all of the propellant with it. Thus, the thruster wastes valuable fuel, resulting in a lower specific impulse.

One way to achieve a more uniform gas breakdown is to pre-ionize the propellant using microwave energy. This concept is called a microwave gas-fed pulsed plasma thruster (MiGfPPT). Inside the pre-ionization chamber, a magnetron emits microwave radiation that heats the fuel into a plasma state. The plasma enters the cavity between the anode and cathode through small holes. Since plasmas are conductive, a current sheet forms between the anode and cathode. Figure 1b shows an axial slice of a MiGfPPT.

My experimental work for the summer was to fire a microwave initiated pulsed-plasma thruster that had been designed by a previous undergraduate. As the former student had not left any notes, I worked to recreate the thruster setup from scratch. After eliminating problems with the magnetron and its high-voltage power supply, I successfully fired the thruster using Argon gas. I measured the voltage and current between the anode and cathode as a function of time and compared the results with the previous experimenter.

As Figure 2 shows, a large current (~1,100 A) passes through the plasma in a time window of about 10 microseconds. The voltage difference between the anode and cathode sharply decreases during this time, which continues until the two electrodes swap polarity. This seems to be the effect of an under damped circuit. In addition, the voltage trace shows spikes caused by the power supply. These random events made it difficult to determine whether voltage oscillations

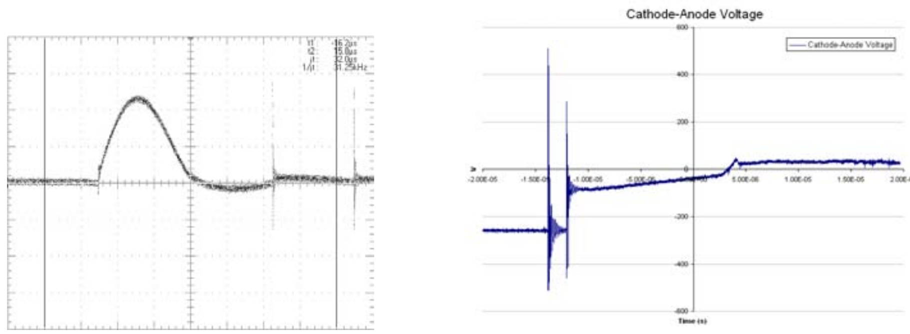

Figure 2: Data from firing the MiGfPPT at 250V and gas pressure of 9 Torr. (a) Current trace showing a discharge lasting 10 μs. 4 μs per horizontal division, 500 A per vertical division. (b) Voltage between anode and cathode during firing.

were caused by the power supply or the plasma. Overall, my experimental data matched existing data, though in some areas it revealed differences. For example, the peak current in my trials was about half the peak current in earlier studies. This experimental work gave me valuable hands-on experience and showed me the process of conducting a scientific or engineering experiment.

3 Diagnosis: Current Sheet Uniformity

As stated before, the uniformity of a pulsed plasma thruster's current sheet greatly affects its efficiency. Although there are high-speed photographs of current sheet formation, there is no quantitative measure of current sheet uniformity. Creating a measure of uniformity would allow us to analyze how a current sheet evolves in the thruster, as well as enabling comparison between different types of thrusters and different operating conditions.

To determine the current sheet uniformity, one must first photograph a GfPPT firing. Next, one would input the photograph (such as the one shown in Figure 3) into a computer, which would follow an algorithm to compute uniformity in the current sheet. As long as the camera settings do not change, these results can be compared across thruster types and operating parameters.

The algorithm I created lets the user specify the location of the current sheet in the image. Next, it divides the current sheet into concentric rings, and computes the standard deviation of all brightness values in each ring. Finally, the program averages these standard deviations over all the rings, weighted by area. In effect, this algorithm computes azimuthal standard deviation, which is appropriate because many thrusters have ring-shaped features (such as gas injection holes) that are not caused by current sheet irregularities.

Instead of displaying the result as a standard deviation, the program converts it into a number–Percent Uniformity–before displaying it to the user. This step

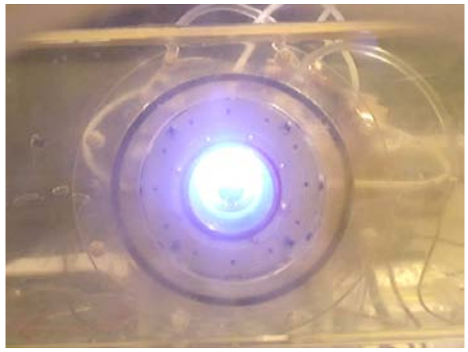

Figure 3: A current sheet produced during the firing of the MiGfPPT, captured from a frame of digital video.

scales the standard deviation value between a completely uniform sheet (zero standard deviation) and a completely non-uniform sheet (random black and white pixels). Another feature of the program is that it lets the user control which color channels in the image are used. Since each color photo can be decomposed into three sets of color data (red, green, and blue), it is valuable to be able to take data from the color data that shows the most detail.

4 Modeling: Filament GfPPT

One idea for a GfPPT is to use a heated filament to initiate gas breakdown instead of spark plugs or microwaves. When a wire is heated, it begins to shoot off electrons in a process called thermionic emission. The filament GfPPT would use these electrons to effect undervoltage breakdown of its fuel.

To determine the feasibility of this kind of thruster, I modeled the characteristics of a wire filament as a current passes through it. First, I used the heat conduction equations from thermodynamics and a surface control volume to derive the temperature of the wire surface as a function of time. Then, I used this temperature data to calculate the thermionic emission of electrons.

To create the most realistic model possible, I included the properties of the filament material, tungsten, as a function of temperature. Like any substance, properties such as resistivity and thermal diffusivity change as the filament is heated. Because thermionic emission increases rapidly with temperature, the filament should be kept as hot as possible without melting or evaporating.

One way of pulsing this type GfPPT would be to switch the current through the filament on and off. However, when I tested this idea with my model, I found that the thermal inertia of the filament (even for a wire as thin as 0.025 mm) severely limited the maximum pulsing frequency. In other words, the time it takes to heat up the wire limits the rate at which its temperature can be pulsed. The thrust of any pulsed plasma thruster is limited by the pulsing frequency

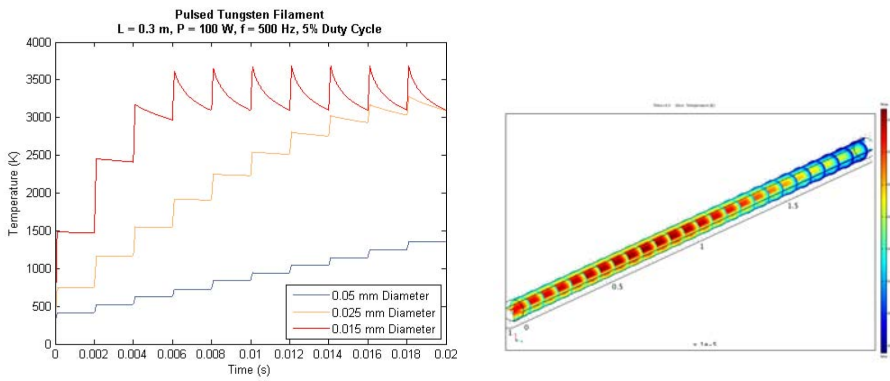

Figure 4: (a) Temperature of a filament when current is pulsed through it. (b) Filament modeled in the Cosmol Multiphysics software suite.

(more pulses per second produce more impulse), and thus I found this mode of operation to be unfeasible.

5 Conclusions

My summer research was a rewarding and intellectually stimulating experience. Simply working alongside people engaged in everything from abstract numerical simulations to the most practical experimental work gave me a great perspective of academic scientific research. I enjoyed sampling across this spectrum in my projects; working on the MiGfPPT showed me the practical difficulties and excitement of experimental work, while modeling the filament gave me a chance to put my math and physics classes to the test. I am very grateful for the opportunity the PPST has given me, and for the support and inspiration of Professor Edgar Choueiri. I would also like to thank Jimmy Cooley, the graduate student who helped me with every aspect of my project, and the rest of the Electric Propulsion and Plasma Dynamics Lab, for their guidance and wisdom.