Design and Testing of a Low Power Radio-Frequency Electrothermal Thruster

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Previous proof-of-concept work on a low power 100-watt radio-frequency electrothermal thruster (RFET) showed that, while the concept is feasible, there was little heating of the helium propellant gas and, thus, minimal thrust generated. The reason for this was theorized to be that the plasma generated by the RF current was not being excited into the proper mode necessary for high levels of power coupling. While the transition for inductively coupled plasma from electrostatic to electromagnetic mode occurs at a power level higher than 100 watts, once electromagnetic mode is achieved, it was shown that the electromagnetic mode could be maintained at the desired 100-watt power level. Work was done to find exact transition powers from electrostatic to electromagnetic mode, as well as characterization of thruster performance at 100 watts once electromagnetic mode was achieved.

Nomenclature

g	=	gravitational acceleration
I_{sp}	=	specific impulse (s)
$\dot{m}$	=	mass flow (kg/s)
M_a	=	molecular mass (kg)
P_e	=	exit pressure (Pa)
P_h	=	hot fire pressure (Pa)
P_c	=	cold flow pressure (Pa)
R	=	universal gas constant
T_h	=	hot fire temperature (K)
T_c	=	cold flow temperature (K)
u_e	=	exhaust velocity (m/s)
γ_h	=	specific heat ratio at high temperature
γ_c	=	specific heat ratio at room temperature

I. Introduction

THE need for high efficiency electric propulsion (EP) increases with the demand that is now being placed on the satellite industry to reduce costs for the growing telecommunications and global positioning industries. Along with increased efficiency, reducing the amount of mass and energy that are consumed by essential systems such as propulsion will allow for more profit geared communication or application based payloads to be included in spacecraft.

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In order to address this need, The Pennsylvania State University has been developing a low power radio-frequency electrothermal thruster (RFET) in order to improve on current electric propulsion options. The RFET is a designed to operate at 100 W of power and applies the concept of an inductively coupled plasma to heat a propellant gas to be used to generate thrust. Like most EP applications, the amount of thrust will be small compared to chemical alternatives, however, the tradeoff in I_{sp} as well as thruster lifetime make it a viable alternative for attitude adjustment, station keeping or for deep space missions that would require thousands of hours of run time. The RFET is desirable because unlike other electrothermal devices such as arcjets or Hall thrusters, the plasma does not erode the mechanical parts, thus allowing for little to no wear on thruster parts.

II. Experimental Overview

A. Objectives

The proof of concept RFET device was completed and described in Refs.1 and 2. The preliminary experiment showed that, while the plasma lit in the chamber, it was reflecting a majority of the power into the coil and not adding a significant amount of energy to the propellant gas. This is due primarily to the plasma operating at the low power electrostatic or E-mode. In order for the thruster to operate at high efficiency, a method needs to be found to increase the coupling efficiency with the plasma. This can be accomplished by causing the plasma to switch modes from the electrostatic or E-mode to the electromagnetic or H-mode. Current studies in RF plasmas have shown that there may be several ways to accomplish this, either by adding more power or possibly by altering the frequencies used.[3-8] Current research also shows that, while initially causing the plasma to switch over to H-mode requires higher power levels, once the H-mode is induced, power may be reduced while maintaining the H-mode, thus keeping the overall operating power needed down to the desired 100 W.[6] This transition and the viability of the coupling efficiency is the main focus of the RFET research presented in this paper.

B. Overview of Experiment

Since the original experiment was disassembled, the first step was to recreate the original experiment and duplicate the results. This was done using the original thruster design, but with improved tuning equipment for impedance matching to produce a more stable plasma and get more accurate power measurements. Once the original experiment was duplicated work began on improving upon it by finding a way to transition from E-mode to H-mode. This investigation was done by looking at increasing the frequency of the RF current used, and if that failed, then increasing the power. Original work was limited to only 100 W of input power and it was believed that more power was needed to induce the transition from E-mode to H-mode. Once H-mode was achieved, characterization of the H-mode plasma was measured to see if the H-mode could be sustained at 100 watts. Finally, chamber pressure measurements were taken under power in H-mode to see if there were any significant increases in chamber pressure, indicating the heating of the propellant gas and better coupling efficiency than was found in the E-mode.

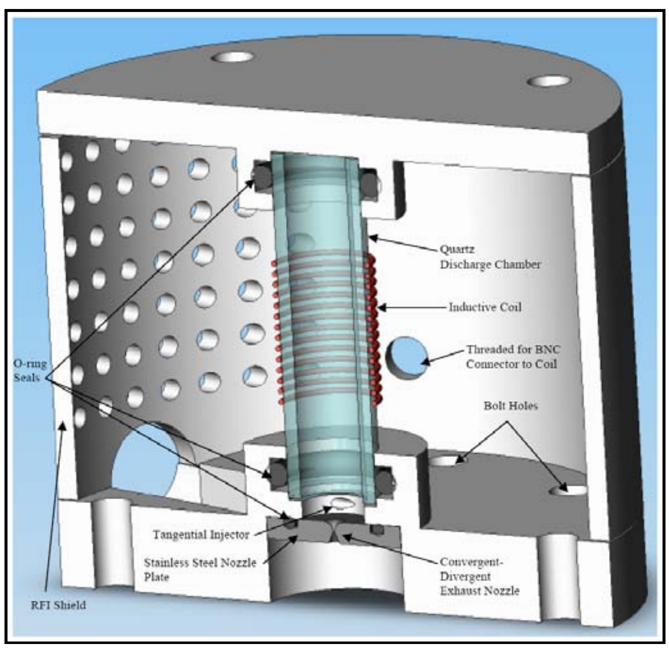

Figure 1. Diagram of RFET design.

C. Methodology

As previously shown in Refs. 1 and 2, the operational theory of the RFET was sound. A plasma was induced using the existing RFET design; however, there was no appreciable heating of the propellant gas. The logical first step in furthering the RFET research was to recreate the original experiment and verify its results. With reference to Fig.1, the thrust chamber was assembled from four main parts. A quartz tube was used as the chamber for this experiment. The chamber was capped by two aluminum housings. On one end, there were two injectors that injected helium into the chamber tangentially, causing a swirl of the gas in the chamber. Finally, the quartz chamber was wrapped by 18-AWG magnet wire. The wire was then also wrapped around a 1:1 balun (not pictured in Fig. 1). The balun was used to provide improved impedance matching from the power source to the coil.

D. Measurements

Data on both pressure and electrical power were needed in order to verify the operational viability of the RFET. RF interference with the equipment was a challenge in this first stage experiment, so attempts were made to limit this problem by implementing the RFI shield that was designed previously. However, implementation of this became a challenge due to size constraints and so a larger shield was constructed and used to eliminate interference. Forward and reverse power measurements were made using two Mini-Circuits PWR-6G+ USB power meters attached to the circuit via a RF directional coupler.

The coupler is attached between the amplifier and the MFJ 989C versa-tuner, and data from the power sensors is collected via software. Pressure measurements are made in two places. Chamber pressure is measured by an Omega pressure transducer attached to the plasma chamber outputting to a digital meter. Vacuum pressure is measured by a Hasting capacitance manometer attached directly to the vacuum cross into which the thruster is exhausting and outputting to a digital meter.

III. Experimental procedure and Results

A. Experimental Setup 1 and Results: Reproducing Rutledge's Experiment

To replicate the results presented in Ref. 7, the thruster setup described above was attached to a vacuum cross and air was evacuated using a vacuum pump to lower the chamber pressure. Once the air was evacuated, helium was pumped into the chamber using a UNIT 500-sccm nitrogen mass flow controller. A correction factor of 1.45 was needed to adjust the actual mass flow of hydrogen through a nitrogen mass flow controller. This correction factor was used in measuring the mass flow data. The lowest amount of mass flow that was possible was a 20% flow, approximately 0.43 mg/s of helium. This minimum mass flow did not increase the pressure of the chamber at first. A signal was then generated at 13.56 MHz by an Agilent 6080A signal generator. The signal was then amplified using an ENI 2100L 100-W RF amplifier.

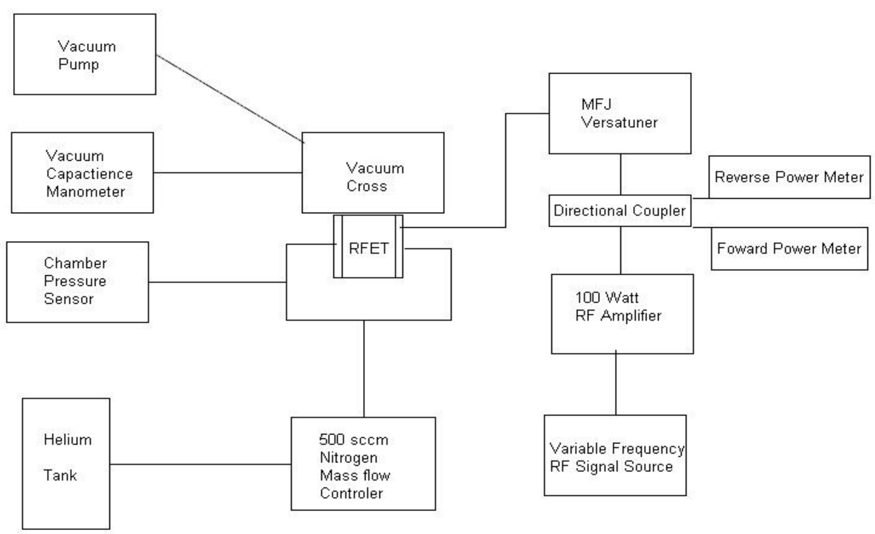

Figure 2. Experimental setup 1.

One of the main challenges in the previous setup was impedance matching. At powers above 80 watts, matching of the impedance of the signal source to that of the coil became difficult. To improve the matching and thus increase the amount of input power, impedance matching was done using a MFJ signal tuner. This allowed stable operation at the maximum output of the ENI amplifier and at variable mass flows into the plasma chamber. This setup is shown in Fig. 2.

In order to establish a baseline pressure in the chamber during mass flow, measurements need to be taken without power to the thruster. Using the vacuum pump, vacuum pressures of 0.0087 psi were achieved, allowing a chamber pressure of around 0.02 psi. Helium gas was then pumped into the vacuum chamber using the 500-sccm mass flow controller. Cold flow readings were taken for mass flows of 0.43 mg/s to 1.08 mg/s. Cold flow data is provided in Fig. 3.

Once cold flow data was taken, helium was returned to the initial flow rate of 0.43 mg/s, which was the maximum flow rate that made no change in the chamber pressure. RF power at a frequency 13.56 MHz was then applied to the coil using the function generator until the plasma lit. The plasma typically initiated around 25–30 watts of power, a large improvement over the previous experiment, which typically needed powers of around 80 watts in order to initiate the plasma. Additional power was supplied to the coil up to the maximum limit of the amplifier, which provided readings of around 100 watts forward power. Once this setup was stable, we verified that the plasma was operating in E-mode by taking powered pressure readings at 70 watts and a range of mass flows from 0.43 mg/s to 1.08 mg/s. The data in Fig. 4a and 4b reflect results similar to previous testing. We saw little increase in chamber pressure over the cold flow readings, verifying that the plasma was adding little energy to the propellant gas.

B. Experimental Setup 2 and Results: Initiating H-Mode Transition via Frequency

Equipment in the initial setup was hampered by a few limitations. The Agilent function generator had a maximum frequency of 15 MHz. Also, the maximum power that could be provided by the RF amplifier was 100 W. Even at very low chamber pressures of 60 Torr, at least 140 W of power was needed to initiate H-mode; however, the research of Ref. 7 showed that it was possible to achieve lower breakdown voltages by using higher frequencies. This was decided to be the first avenue of research for reaching the H-mode transition. The Agilent signal generator was exchanged for a Fluke 6080A which is capable of frequencies up to 1 GHz. Power measurements were made using the same setup as above, as was circuit tuning. Data was gathered for power of 100 W over a range of frequencies from 13.56 MHz to 21 MHz. Any frequency higher than 21 MHz was unable to initiate a plasma due to problems with impedance matching.

While increasing the frequency of the input signal did seem to lower the initiation of the plasma slightly, even at the highest powers achievable by the ENI amplifier, the transition from E–H mode was not possible. Power measurements show that reflected power remained between 40 and 80% and there were no substantial increases above cold flow pressures. These results duplicated what was seen in Experiment 1 showing that the frequency was not a sufficient method of initiating H-mode.

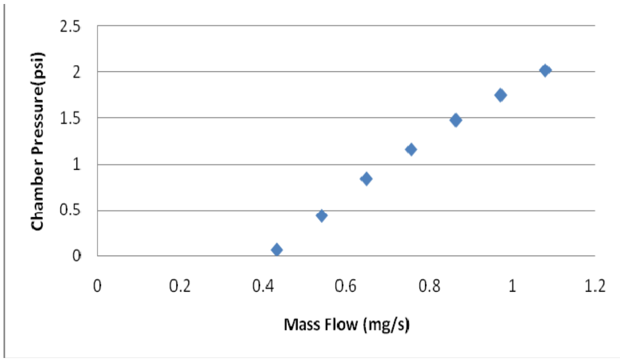

Figure 3. Cold flow pressure data for experiment 1.

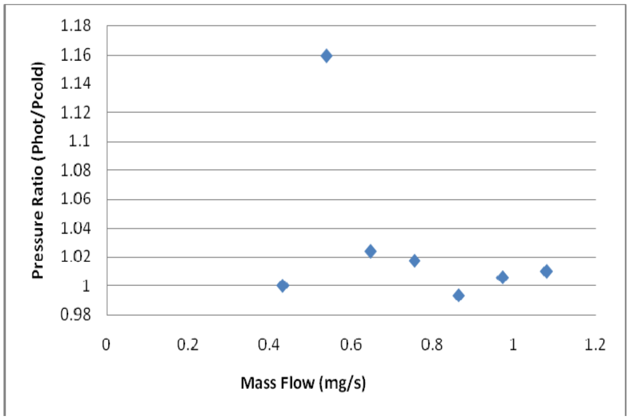

Figure 4a. Pressure ratio vs. mass flow for experiment 1.

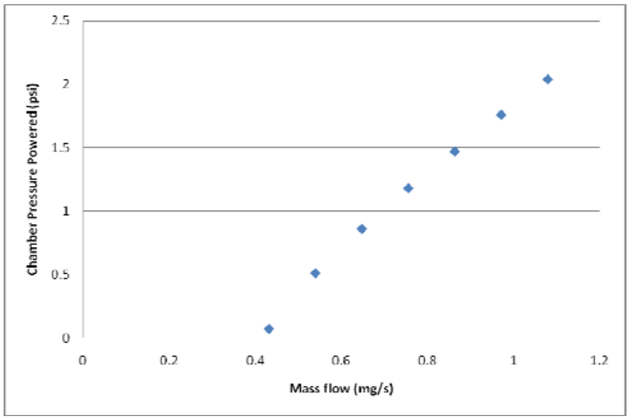

Figure 4b. Chamber pressure (powered) vs. cold flow experiment 1.

C. Experimental Setup 3 and Results: Initiating H-mode Transition via Increased Power

The final experimental setup required adding an additional RF amplifier to increase the input power over the 100-W maximum of the ENI amplifier. An Ameritron AL-1200 RF amp was used to increase the input power to higher levels. The final setup shown as a schematic in Fig. 5 shows that the AL-1200 amplifier was inserted between the ENI amplifier and the MFJ tuner. The MFJ tuner was also replaced with an MFJ auto-tuner, making the impedance matching of the circuit even more efficient. First tests were conducted to see what power level would be needed to initiate E–H mode transition. Once that power level was established, cold flow measurements were taken, and then hot fire measurements for the same mass flows were taken as above in experiment one.

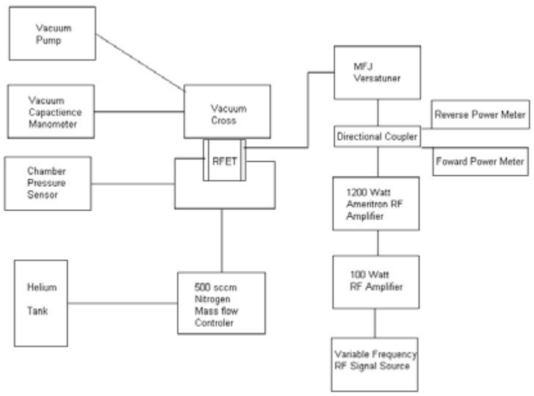

Figure 5. Experimental setup 3.

In order to ensure more efficient propellant heating, the threshold of the transition from E to H mode needed to be established. Power levels over the 100 watts that would be the operational power of the thruster need to be used to induce the H-mode plasma. Once this has been achieved, power could be reduced to operational power at a much higher power coupling efficiency.

H-mode transition would be easier to obtain at lower chamber pressures, so the minimum mass flow of 0.43 mg/s of helium was injected into the chamber. This resulted in a chamber pressure of 0.03 psi. Power was then applied to the coil and slowly increased. The transition from E-mode to H-mode would be marked by a drastic reduction in the reflected power and thus higher power absorption from the plasma. Transition occurred at 140 watts of forward power, which created a cascade effect that reduced the measured forward power down to 120 watts and the reflected power percentages from 45–50% down to 12–20%. Once this was achieved, power was reduced to 100 watts to see if the plasma would remain in H-mode, which it did. These results agreed with the results of Ref. 4 in that transition back to E-mode from H-mode occurred at a much lower power than the transition from E-mode to H-mode. Fig. 6 shows the plasma in E mode, Fig.7 shows the plasma operating H-mode and Fig. 8 shows reflected power versus input power of both the E-mode and H-mode.

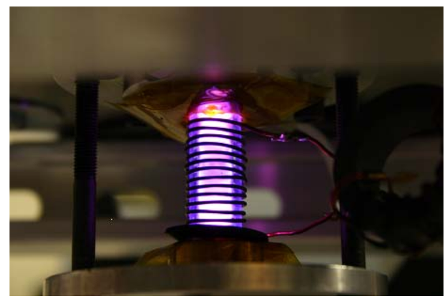

Figure 6.Operation in E-mode.

With the results showing that the plasma was sustainable in the H-mode at low pressures, testing needed to be done to see if there was any increase in chamber pressure and, thus, increase in propellant temperature that would generate thrust. Cold flow chamber measurements were again taken to establish a baseline of mass flow versus chamber pressure. At this time, vacuum pressure measurements were also taken to establish baselines for determining theoretical thrust and exit velocity calculations. These cold flow measurements were done in the same manner as in Experiment 1 with similar results show above in Fig. 9.

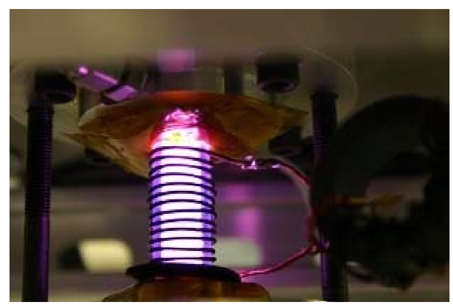

Figure 7.Operation in H-mode.

Once cold flow data was taken for a baseline, hot fire measurements were taken. The pressure was kept at its lowest point of 0.02 psi and then a plasma was initiated by adding power to the coil. The power was then increased to 140 watts so that transition to H-mode occurred. Once H-mode was achieved, the power was lowered back down to 100 watts and chamber and vacuum pressure measurements were taken at mass flows of He from 0.43 mg/s to 1.61 mg/s. With the plasma in H-mode, there was a marked pressure increase in the chamber indicating that there was significant heating of the propellant gas. Higher temperatures were also evident due to thermal breakdown of the insulation on the RF coil, necessitating its replacement for verification of the pressure results. Heating results can be seen in Figs. 10 and 11.

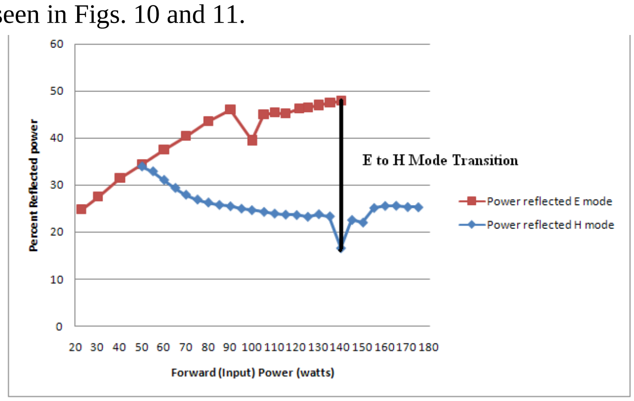

Figure 8. Percent reflected vs. input power.

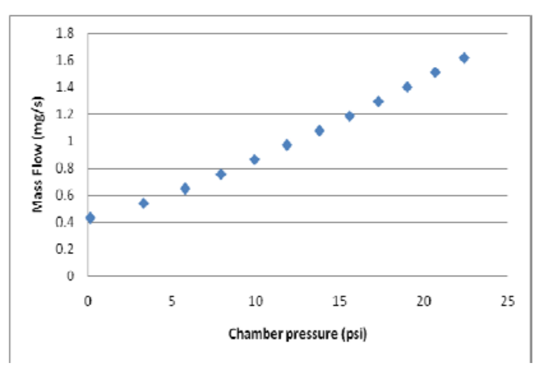

Figure 9. Experiment 3 cold flow data.

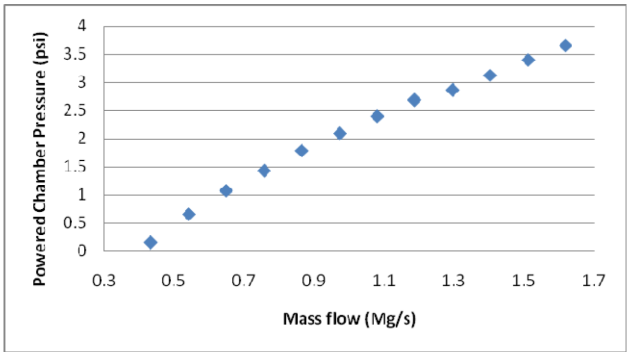

Figure 10. Powered mass flow vs. chamber pressure.

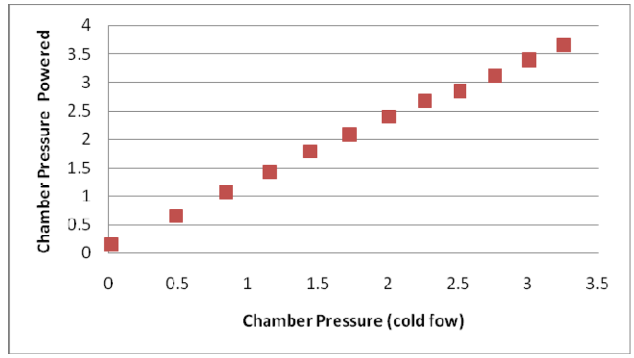

Figure 11. Cold flow pressure vs. powered pressure.

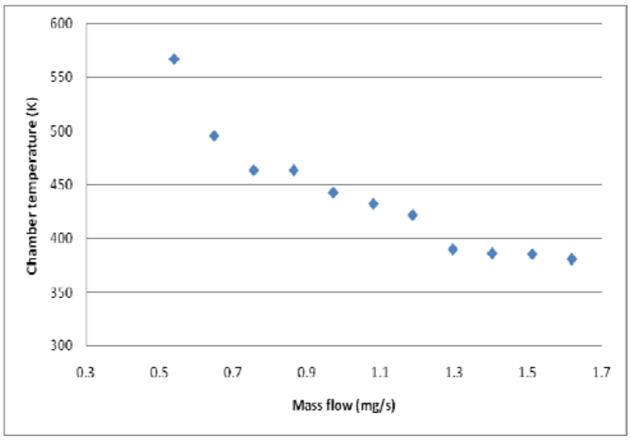

Figure 12. Percent reflected vs. input power.

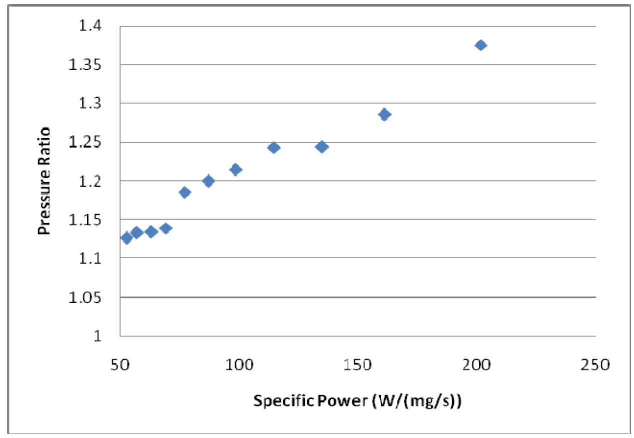

Figure 13. Specific power vs. pressure ratio.

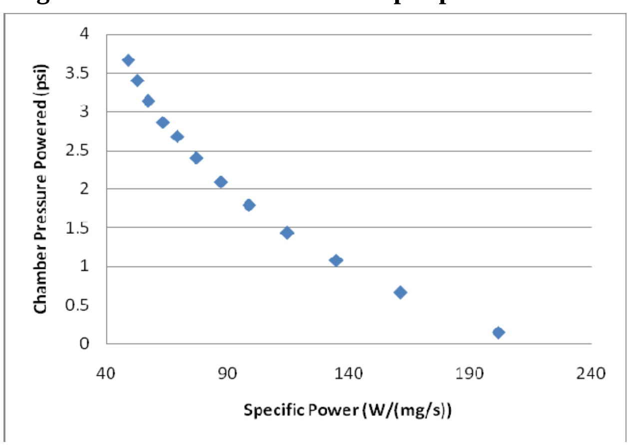

Figure 14. Specific power vs. powered chamber pressure.

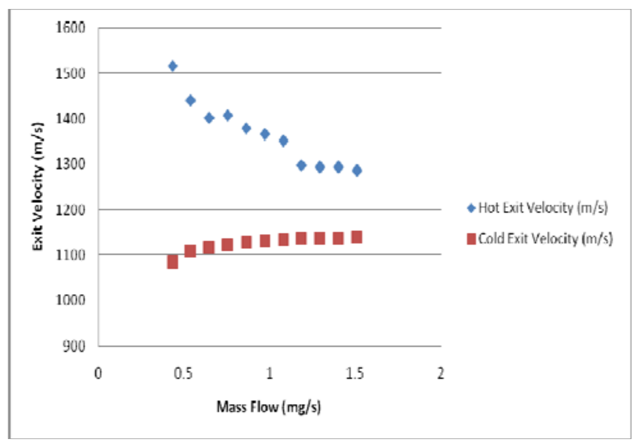

Figure 15. Mass flow vs. hot and cold calculated exit velocities.

IV. Discussion of Results

A. Discussion of Results

Figures 11 through 15 show that, in H-mode, there is heating of the propellant gas. This can be seen by the increase in chamber pressure from the cold flow tests to the hot fire tests. In order to calculate the temperature, we used the ideal gas law and ideal rocket equations to calculate chamber temperatures using the formula[9]

$$\frac{T_h}{T_c} = \left(\frac{P_h}{P_c}\right)^2 \left[\frac{\gamma_h \left(\frac{2}{\gamma_h + 1}\right)^{(\gamma_h+1)/(\gamma_h-1)}}{\gamma_c \left(\frac{2}{\gamma_c + 1}\right)^{(\gamma_c+1)/(\gamma_c-1)}}\right]. \tag{1}$$

Since the calculated temperatures did not approach breakdown temperatures for helium, the γ terms were assumed to be equal and were dropped. Fig. 12 shows the calculated temperatures as a function of mass flow. Heating of the helium reduces with increased mass flow, as expected, and was observed previously; however, chamber temperatures varied from 567 K to 380 K. This shows that the transition to H-mode increased power input into the plasma significantly. The trend of increased mass flow lowering temperature can also be seen with plots of the specific power as seen in Figs. 13 and 14. This shows that increasing the mass flow decreases the amount of power absorbed by the plasma, which follows with previous per mass results and with theoretical predictions.

With the above results showing that there was some heating done by the plasma, theoretical performance of the thruster could be analyzed. Using the ideal rocket equations we can calculate exhaust velocity and I_{sp} values. Velocity is calculated using the isentropic rocket relationship between pressure, temperature and exhaust velocities in the equation[9]

$$u_e = \sqrt{\frac{2\gamma R}{(\gamma - 1)} T_c \left[1 - \left\{\frac{p_e}{p_c}\right\}^{\frac{\gamma-1}{\gamma}}\right]}, \tag{2}$$

where γ is the ratio of specific heats for helium, R is the universal gas constant, M_a is the molecular mass of helium, T_c is the calculated chamber temperature, P_e is the exit pressure or the pressure in the vacuum cross, and P_c is the chamber pressure. Exit velocities were calculated for cold and hot fire testing and can be seen plotted in Fig. 15. As the figure shows, there is a marked increase in exit velocity in the powered mode over the cold flow mode. This data can also be used to calculate the increase in I_{sp} from the cold to hot data. I_{sp} is a measure of the efficiency of the rocket and is calculated by the equation

$$I_{sp} = \frac{T}{\dot{m}_g g}. \tag{3}$$

The highest change in cold to powered I_{sp} was calculated to be 48 s. Actual I_{sp} values for the powered testing ranged from 152 to 128 s. While these results may seem to be disappointing at first, they do show that there was heating due to the plasma when the plasma was in H-mode.

V. Summary and Future Work

Results of the experimentation on the RFET have shown that H-mode transition is achievable at moderate power levels. H-mode can be maintained at the operating power of 100 watts, which shows promise for heating of propellants to useable I_{sp} and thrust levels. Hot fire data shows that untuned, moderate pressure increases at low mass flows were achievable. Powered to cold flow pressure ratios of near 1.4 where achievable, thus showing that further investigation into the RFET might yield favorable results for an operating thruster. Further work should be done on the RFET focused on tuning the plasma to accept the maximum power from the RF current and minimizing heat losses.

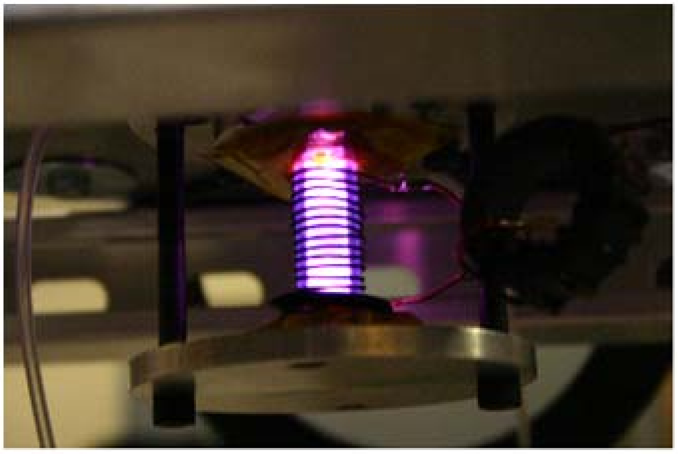

Figure 16. Powered H-mode operation showing anomalies at the top and bottom of the quartz chamber.

Based on the results that show that there was significant heating when the plasma transitioned to H-mode, as well as the fact that H-mode can be sustained at 100 watts once transition has occurred, future work should focus on increasing the power coupling efficiency to the plasma. Increasing absorbed power would increase the chamber temperature of the propellant gas. The experimental setup, while more stable than the original setup, was still very touchy. Occasionally, the plasma would extinguish for no apparent reason or the tuner would lose impedance matching, which would cause fluctuations in the plasma and in the absorbed and/or reflected power. This temperamental nature of the setup shows several areas that can be investigated to increase the efficiency of the thruster.

The coil would be a primary source for further research. The coils that were used were hand wrapped and not precise in their spacing or construction. Therefore, a more uniform coil could lead to a more stable RF current, a more stable magnetic field, and a more stable plasma. Evidence of this can be seen in Figure 16, which shows that near the top and bottom of the chamber, even in H-mode, there are still brighter regions that may indicate an E-mode plasma. The figure also shows the imprecise nature of the coil construction. The coil which is 18 AWG size should probably be increased to 16 AWG or larger. This would allow for better power handling and better heat dissipation.

Another avenue of investigation is the aluminum that was used to construct the top and bottom housings. As can be seen in Fig. 16, the top of the plasma in the chamber is brighter than the middle parts. This could be due to flow effects of the helium injectors, or it could be an indication that the aluminum is concentrating the B field and creating an E-mode plasma. This could be a potential source of loss that might be avoided by constructing the housings out of a less conductive material. While altering the frequency did not help in the E-to-H-mode transition, further investigation into this as a method of increasing power transfer into the plasma may yield results.

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