Use of Ammonia as a Propellant in a 17.8-GHz Microwave Electrothermal Thruster

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In this paper, we describe the feasibility of using ammonia as a propellant in a 17.8-GHz microwave electrothermal thruster. Microwave electrothermal thrusters are a type of electric propulsion that use microwave energy to heat a gaseous propellant to plasma temperatures followed by nozzle expansion, thus generating thrust. Microwave electrothermal thrusters produce higher specific impulses than chemical thrusters, which make them attractive for in-space propulsion. This feasibility study examined the performance of a low-power microwave electrothermal thruster using ammonia as propellant. Using the measured hot-fire-versus-cold-flow-stagnation-pressure ratio, specific impulse is calculated during the hot-fire test as a function of input power and mass flow rate. Based on the hot-fire tests, stagnation pressure ratios of 1.31, 1.33, and 1.34 for mass flow rates of 0.11 mg/s, 0.15 mg/s, and 0.17 mg/s were achieved at input powers of 24.2 W, 35.9 W, and 40.7 W, respectively.

Nomenclature

a = cylinder radius
h = height of the resonant chamber
I_{sp} = specific impulse
MW = molecular weight of the propellant
P_{for} = forward power
P_{ref} = reflected power
P_0 = chamber pressure
t = thickness of the dielectric insert
T_0 = chamber temperature
z = longitudinal or the y direction
ρ = radial direction
γ = specific heat ratio

subscripts
c = cold flow
h = hot fire

I. Introduction

Microwave electrothermal thrusters (METs) work on the principle of generating plasma in a propellant through the use of microwaves followed by a gasdynamic expansion through a converging–diverging nozzle to create

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thrust.[1] A schematic diagram of an MET is shown in Figure 1. Microwaves are fed into the resonant cavity—where plasma formation takes place—by a candlestick antenna that is located at the bottom of the cavity. A transverse magnetic TM^z_{011} mode is established, which concentrates the electric field at the antenna and the nozzle ends of the cavity. Figure 2 shows the resultant electric and magnetic fields inside the resonant cavity. Plasma generation occurs at the nozzle end, which is a region of highest electric field intensity.

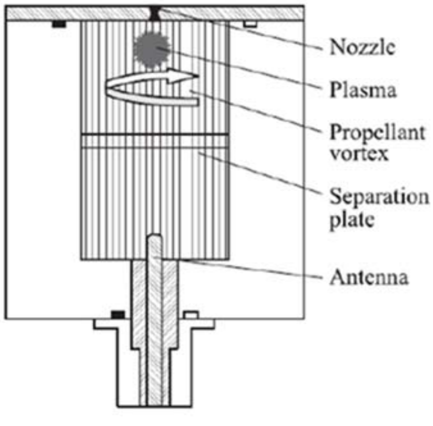

Figure 1: MET Thruster cavity cross section.

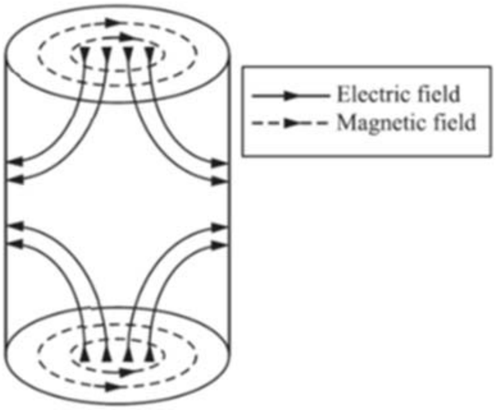

Figure 2: TM^z_{011} mode in a circular cavity.[2]

Through the propellant ports, propellant is injected into the cavity such that it swirls around the cavity, forming a propellant vortex, which confines the plasma, stabilizes it, and keeps it away from the cavity walls, thus preventing wall erosion and heat loss. To facilitate the plasma ignition, the chamber pressure is lowered below atmospheric pressure. The plasma heats the incoming propellant and accelerates it out of the nozzle to produce thrust.

Research on METs has been progressing since the 1980s at The Pennsylvania State University, initially by Micci, Maul, and Balaam.[3] The first prototype version of the thruster was fabricated by Sullivan and Micci.[4] It operated at a frequency of 2.45 GHz with an input power of 1 kW to 2.5 kW with cavity dimensions of 15.75 cm in length, which could be adjusted, and diameter of 10 cm. That MET version served to investigate the plasma formation and its stability inside the resonant cavity, the effect of different propellants on plasma formation, and the characteristics of the cavity's mid-plane dielectric insert. Subsequently, additional versions of the thruster were designed to operate at several other frequencies including 7.5 GHz,[5] 14.5 GHz,[6] and 30 GHz.[7] Increasing the resonant frequency decreases the overall size of the thruster and the input power required to ignite a plasma.

Recently, CubeSats are becoming ubiquitous for space applications due to their small size, cost effectiveness, and decreased complexity compared with larger satellites. However, efficient and high performing propulsion systems for CubeSat attitude control and orbital maneuvering are still lacking. Solid rocket motors are less efficient and lack the ability to relight and liquid rocket engines require complex plumbing—and both provide lower performance in terms of I_{sp} than can be achieved with electric thrusters. An MET of small size could play an important role in providing propulsion capability for CubeSats, thus facilitating higher specific impulse and more change in velocity (delta-V) for extended missions and mission flexibility.

METs are extremely flexible in terms of propellant. In this paper, we focus on ammonia as a propellant for the following reasons: it is readily space storable, considered as a green propellant by NASA due to its low toxicity, and, because of its low molecular mass, can offer high exhaust velocity at the same power. This paper demonstrates feasibility by providing data on the variation with input power of the stagnation pressure ratio before and after plasma generation.

II. Thruster Design

The thruster body of an MET is essentially a cylindrical microwave resonant cavity. The dimensions of the cavity dictate the resonant frequency and the resonant mode in which the MET operates. In the present configuration, the thruster was designed to resonate in the TM^z_{011} mode and operate in the K_u microwave band. The aforementioned parameters were chosen since the TM^z_{011} mode is the optimum mode for plasma formation near the cavity's nozzle and the K_u band facilitates access to a wider range of commercial-of-the-shelf (COTS) components. A target frequency of 17.8 GHz was chosen, since it falls within the K_u band (12 GHz to 18 GHz), while making the thruster as small as possible, which in turn allows us to achieve plasma ignition at low input power.

The 17.8-GHz MET has a dielectric plate positioned at the mid-plane of the cavity in order to preferentially reduce the pressure in the nozzle portion of the cavity, which causes plasma formation to occur in that half of the thruster, i.e., at the nozzle and not at the antenna end. Figure 3 shows a generalized schematic of the resonant cavity with the dielectric plate. Quartz with thickness of 0.0625 inches (1.59 mm) was selected for the dielectric because of its ready availability and low microwave loss. The cavity dimensions for the 17.8-GHz resonant frequency are 21.1 mm in height with radius of 6.8 mm, giving a height-to-radius ratio of 3:1. This ratio was chosen because of its effectiveness in previous MET models as well as expected performance based on COMSOL Multiphysics simulations.[8]

Regarding the other elements of the thruster head, the propellant ports are 0.0059 inches (0.15 mm) in diameter, in order to increase the incoming propellant velocity in the chamber to ensure the formation of a propellant vortex. The nozzle, which was straight and not converging–diverging, was also of the same diameter.

Coupling efficiency is an important parameter that determines the amount of microwave power absorbed by the propellant inside the cavity instead of being reflected. For optimum performance, a high coupling efficiency is required, which is obtained by fine tuning the height as well as the shape of the candlestick antenna's conductor. Coupling efficiency is calculated using[9]

$$\text{Coupling Efficiency} = \frac{P_{\text{for}} - P_{\text{ref}}}{P_{\text{for}}}. \tag{1}$$

Variation of reflected power with the antenna height is shown in Figure 4. Based on these measurements, the antenna height was set at 0.71 mm and the actual cavity resonant frequency was 17.90 GHz.

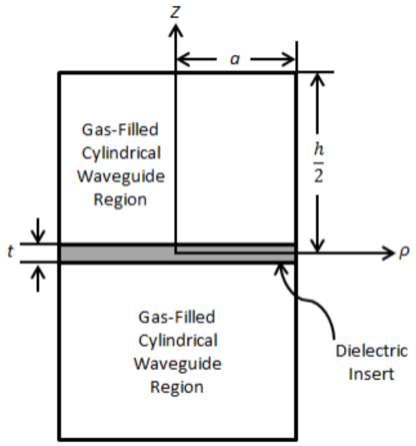

Figure 3: Resonant cavity with a dielectric plate.[10]

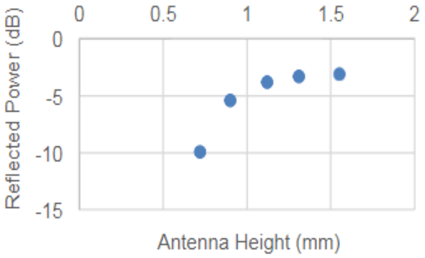

Figure 4: Variation of reflected power with antenna height.[2]

III. Experimental Results

In the experiments described below, the delivery of microwave power is accomplished via a signal generator (Hewlett-Packard 8671B Synthesized CW Generator) that generates a microwave signal at the desired frequency, which is then amplified by a travelling wave tube amplifier (TWTA), a Xicom Technology XTRD-270DBSR. The TWTA has a waveguide output that is converted to SMA via an adapter; this, in turn, is connected a directional coupler for making power measurements, and finally to the antenna on the thruster head via a SMA-to-2.4-mm transition. For the propellant section, the gas flow is regulated by flow meters for helium and ammonia.

The system first is flushed with helium for 30–60 seconds. Once the purge is complete, the helium flow is shut down and ammonia flow is started. The ammonia mass flow rate is set by a Unit Instruments flow controller (UFC-1660) designed specifically for use with ammonia. Cavity pressure is measured by an Omega PX303-050A5V pressure transducer. Once the cavity is evacuated below about 1–2 psi, microwave power is applied. All plasma formation results were performed at a resonant frequency of approximately 17.90 GHz. Figure 5, shows an ammonia plasma through the window of the resonant cavity.

The stagnation pressure ratio acts as a measure of how much microwave energy is absorbed, which in turn is an indicator of the performance of the MET, thus making it an important parameter to be studied in this experiment. A higher stagnation pressure ratio implies a larger amount of microwave energy absorbed by the propellant. The ratio of hot-fire chamber temperature to cold-flow chamber

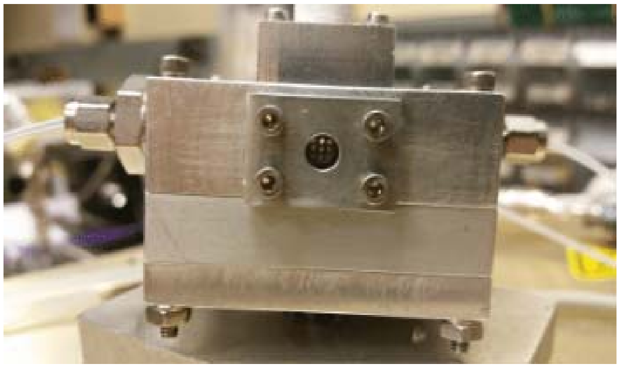

Figure 5: Ammonia Plasma in MET [2].

temperature is directly proportional to the square of the stagnation pressure ratio. This implies that the hot-fire chamber temperature increases with an increase in the stagnation pressure ratio. Hot-fire chamber temperature is calculated by equating the mass flows of the hot and cold flows. The hot-to-cold temperature ratio is calculated as

$$\frac{T_{0,\mathrm{h}}}{T_{0,\mathrm{c}}} = \left(\frac{P_{0,\mathrm{h}}}{P_{0,\mathrm{c}}}\right)^2 \frac{\gamma_\mathrm{h}}{\gamma_\mathrm{c}} \frac{\left[\frac{2}{\gamma_\mathrm{h}+1}\right]^{\frac{\gamma_\mathrm{h}+1}{\gamma_\mathrm{h}-1}}}{\left[\frac{2}{\gamma_\mathrm{c}+1}\right]^{\frac{\gamma_\mathrm{c}+1}{\gamma_\mathrm{c}-1}}} \frac{\mathrm{MW}_\mathrm{h}}{\mathrm{MW}_\mathrm{c}}\,. \tag{1}$$

For calculations herein we assume that the molecular weight and specific heat ratio are the same in both the hot and cold states. Solving for the exhaust velocity and, therefore, the specific impulse, through conservation of energy gives

$$I_\mathrm{sp} \propto \sqrt{\frac{T_0}{\mathrm{MW}}}\,, \tag{1}$$

which implies that I_sp should also increase with the increase in the mean chamber stagnation temperature. From Figure 6 it can be seen that, with an increase in input power, the ratio of hot-fire-to-cold-flow-chamber-stagnation pressure rises. Mass flow rates of 0.114 mg/s, 0.152 mg/s, and 0.171mg/s, respectively as power increases, are shown. Figure 7 shows the variation of estimated hot fire I_sp with input power, whereas Figure 8 shows the variation of estimated hot fire I_sp with specific power.

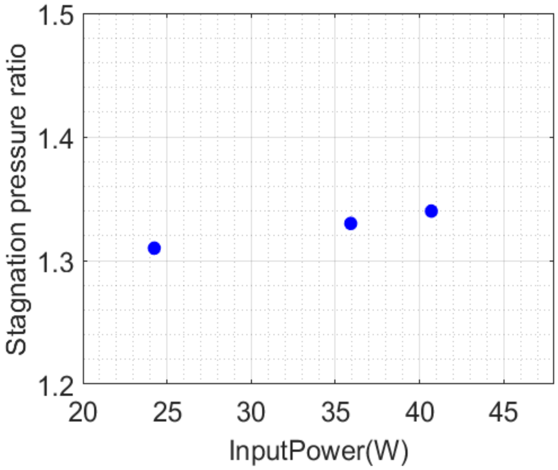

Figure 6: Variation of the stagnation pressure ratio before and after plasma generation with input power.

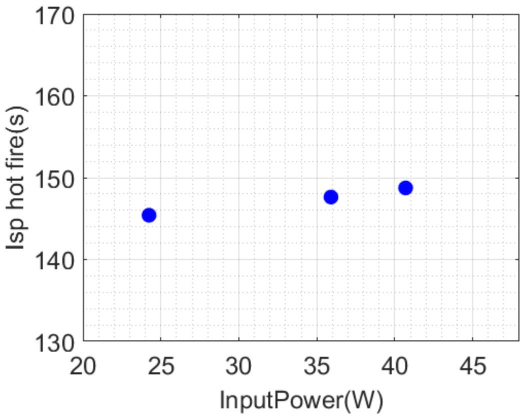

Figure 7: Variation of estimated I_sp with input power.

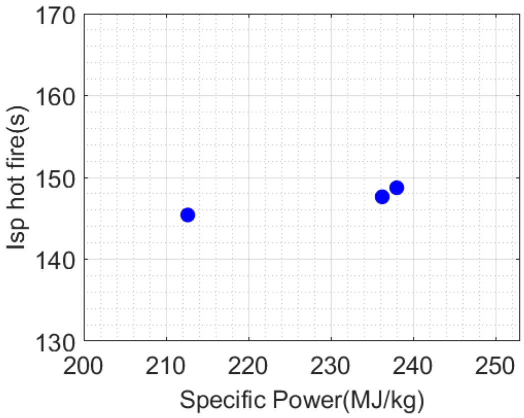

Figure 8. Variation of estimated I_sp with specific power

Hopkins [11] examined ammonia propellant with the 8-GHz MET. Using an input power of 100 W and 150 W, he achieved an estimated I_{sp} of approximately 170 s and 185 s with the mass flow rates of 12.6 mg/s and 13.9 mg/s, respectively. The preliminary results achieved in this feasibility experiment with the 17.8-GHz MET, summarized in Table 1, show better performance in terms of the input power required to obtain a plasma.

Table 1: Summary of test conditions and results.

Po (psia)	Mass Flow (mg/s)	Input Power (W)	Specific Power (MJ/kg)	Po_h/Po_c	Calculated I_{sp} (s)	Estimated Thrust (mN)
1.09	0.11	24.2	212.6	1.31	145.4	0.118
1.18	0.15	35.9	236.2	1.33	147.6	0.139
1.26	0.17	40.7	238.0	1.34	148.7	0.152

Though the results obtained could further be improved, this experiment shows that ammonia plasma can be generated and could be used for propulsion systems in small scale spacecraft, such as CubeSats.

III. Conclusion

Plasma was successfully ignited using ammonia as propellant in the 17.8-GHz MET. Antenna height and the resonant frequency were approximately 0.71 mm and 17.90 GHz, respectively. Experimental results from the hot-fire tests show that stagnation pressure ratios of 1.31, 1.33, and 1.34 for mass flow rates of 0.11 mg/s, 0.15 mg/s, and 0.17 mg/s were achieved at input powers of 24.24 W, 35.91 W, and 40.7 W, respectively. Estimated hot-fire test I_{sp} could be further improved by optimizing the antenna height and its surface condition.

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