LOW-POWER MICROWAVE ARCJET PERFORMANCE TESTING

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Abstract

A microwave arcjet is an electrodeless electrothermal thruster. This design does not suffer from cathode erosion problems of DC arcjets or the chamber temperature limitation associated with resistojets. The system is a closed cylindrical cavity with an antenna connector at one end. The cavity is dimensioned to resonate the first transverse magnetic mode of the microwave signal (TM_{011}). Propellant is tangentially injected and contacts the plasma formed along the longitudinal axis in the nozzle-side of the chamber (opposite to the antenna) as it is exhausted through the nozzle. Prior research has demonstrated good coupling between the incident microwave energy and the propellant gas. The current design uses 7.5 GHz microwave energy at 100 W. Cold flow testing has been performed in ambient conditions with helium and nitrogen. Helium plasma was formed at a chamber pressure of 5 kPa (gauge) with 20 Watts of microwave power. Further testing will use ammonia, nitrogen, helium, hydrogen and water vapor as propellants exhausting into a vacuum.

Nomenclature

a	radial dimension of the cylinder cavity (m)
h	height dimension of the cylinder cavity (m)
p	vertical resonant mode of cavity (equal to 1)
χ_{01}	first zero of the Bessel function, J_0 (equal to approximately 2.405)
μ	permeability of the media within cavity (H/m)
ε	permittivity of the media within cavity (F/m)
τ	Thrust force (N)
m	propellant mass flow rate (kg/sec)
g	gravitational acceleration at sea level (9.81 m/sec/sec)
I_{sp}	specific impulse (sec)
P_{input}	input electrical power from supply (W)

Introduction

Electrothermal propulsion is a working concept in today's world. Lockheed-Martin now offers arcjets as a high-performance alternative for geosynchronous communication satellite North-South station-keeping. However, these conventional arcjets suffer from cathode erosion problems[1] as well as decreased efficiency when operating in lower (~100 W) power ranges[2]. Resistojets also have a material-based limitation that the propellant gas temperature can not exceed the maximum allowable temperature of the heating element or any other propellant-wetted surface.

The microwave arcjet is an electrothermal thruster concept which is electrodeless and therefore doesn't suffer life limitations of electrode erosion. A systematic illustration is given in Figure 1 showing the major components of a microwave propulsion system.

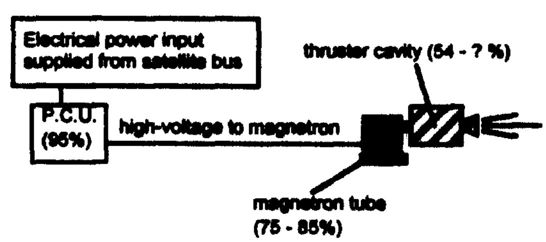

Fig. 1: System illustration with component efficiencies.

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Electrical power from the spacecraft electrical bus is input to a power-conditioning unit (PCU) to convert the available electrical power to high voltage. This high voltage is needed to power a microwave magnetron tube inputting its signal into a properly sized resonant thruster cavity. The cold propellant gas is fed into this engine cavity and heated by contacting the free-floating plasma discharge formed by the microwave energy exciting free electrons. This heating process thus converts the incident electrical power to thermal energy in the gas. A nozzle at the downstream end of the engine provides the final conversion of thermal energy into directed kinetic energy or thrust. This design has been tested and proven to be effective with propellants such as gaseous nitrogen, helium, hydrogen, ammonia and water vapor.

The experimental proof-of-concept studies by Balaam and Micci[3] and Mueller and Micci[4] showed the microwave propulsion concept to be viable. Mueller and Micci[4] used waveguides with internal quartz vessels to bring propellant gas in contact with the resonant transverse-magnetic fields produced within the waveguide at a frequency of 2.45 GHz and power levels of 250 W to 2 kW. Good coupling efficiency between the incident electric power and the absorption and heating of the propellant gas was demonstrated. They showed that a boron-nitride bluff-body could be used to stabilize the plasma location in the propellant flow by creating a point where the fluid velocity down the chamber would exactly balance the plasma discharge's propagation velocity toward the source of microwave energy.

Spectroscopic measurements performed by both Mueller and Micci[4] and Balaam and Micci[3] determined the electron temperature of the plasma to be about 12,000 K. This temperature was found to be relatively invariant with input power, pressure or mass-flow. Balaam and Micci[3] showed the radial profile measurements of the plasma's electron temperature to be fairly constant with input power and pressure. Due to gas pressures of one atmosphere or higher, the electron temperature was felt to be equal to the heavy particle temperature.

Balaam and Micci[3] used swirling of the propellant flow to keep the plasma located in the axial center of the circular waveguide. The axial swirling would create a region of low pressure in the center which would keep the plasma stable. A bluff-body was also used to stabilize the plasma location within the cavity. This method of stabilization was demonstrated with helium plasmas up to 500 kPa gas pressures and coupling efficiencies between 95 - 100% were obtained. Nitrogen also showed similarly good coupling efficiency but was found to be more difficult to ignite due to a greater number of internal energy modes of the diatomic molecules. Although the swirling method did not prove to be as successful as the bluff body, the quality of the swirling motion was probably affected by the geometry of the quartz vessel used.

Sullivan[5] demonstrated a reliable design to produce plasmas in a resonant cylindrical cavity using swirl-injection of the propellant. Sullivan's design, operating in the TM_{011} mode, which better concentrated the electric field along the axis of the chamber, also included the use of a dielectric separation plate to isolate the plasma region from contacting the antenna portion of the engine. Axisymmetric power coupling from the microwave generation source to the microwave arcjet resonant cavity was achieved by aligning a linear probe into the cavity along the longitudinal axis of symmetry of the cylindrical cavity. The linear probe or antenna was simply the termination of the coaxial power transmission line as it entered the cavity. By adjusting the probe's depth into the cavity and adjusting the overall length of the cylindrical cavity, the load impedance of the cavity and the impedance of the transmission line could be matched. When the two system impedances are matched, the maximum amount of power will be absorbed by the cavity/plasma system.

Kline[6] performed actual vacuum chamber thrust stand measurements. Unlike Sullivan's thruster, Kline's magnetron was rigidly mounted into the body of the thruster. This work provided the first vacuum chamber thrust measurements of a microwave arcjet at a frequency of 2.45 GHz and showed a thruster efficiency of 54% (thrust power divided by input electrical power). Kline operated in the 600 to 800 W incident power range and demonstrated a maximum thrust of 303 mN. The work discussed here uses a frequency of 7.5 GHz to provide a smaller resonant cavity to reduce heat losses and provide a more concentrated electric field at lower input power levels (~100 W). The 7.5 GHz magnetron, manufactured by Mictron, is voltage-tunable which allows the frequency of the microwave signal to be fine-tuned by adjusting the supplied voltage to optimize power coupling into the cavity while maintaining a fixed thruster geometry.

The results of Kline showed the efficiency of a microwave arcjet engine to be relatively constant with input electrical power. Figure 2, given below, compares the performance of Hall thrusters[7,8], a conventional arcjet[2] and pulsed arcjets[9] in terms of overall system efficiency versus input electrical along with the projected efficiency trend of a microwave arcjet system with decreasing power. It should be noted that the magnetron/microwave system is a total efficiency figure that includes the losses of all the major components of the microwave propulsion system.

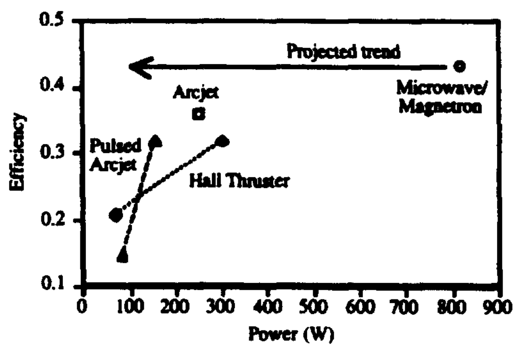

Fig. 2: Comparison chart of electric propulsion system efficiency versus input power level.

The best propellants for this system have been shown to be low molecular-weight, monatomic gases.[5] But for practical purposes, a liquid-storable propellant would be preferred for easy, on-orbit storage. Helium and hydrogen are both difficult to store for extended periods of time due to their extremely low boiling points. Ammonia (NH_3) has been selected for its higher-temperature, liquid-storable properties and low molecular weight. Water (H_2O) is also a good propellant in these respects.

The high-voltage PCU mentioned above is an existing and developed piece of hardware for powering traveling wave tubes (TWT's) used in all communications satellites. These PCU's currently operate at 95% electrical efficiency. Magnetron efficiency at a frequency of 7.5 GHz could be increased to as much as 75% with possible improvements to the magnetron design by the manufacturer, Mictron, Inc.[10]. The efficiency increases with decreasing frequency, becoming 85% at a frequency of 2.45 GHz. It is believed that through greater optimization of the engine cavity and nozzle and lowered frozen flow losses from the propellant, a greater thruster efficiency can be attained.

Experiment

The system introduces the microwave signal into a cylindrical, conductive closed cavity where the first transverse-magnetic mode (TM_{011}) is resonant within the cavity. The cylindrical cavity is sized by Equation 1 from Balanis[11]. μ and ε are the permeability and permittivity constants, where the inverse square root of the product of these two factors represent the phase velocity of the electromagnetic wave.

$$(f_r)_{01p}^{TM} = \left(\frac{1}{2\pi\sqrt{\mu\varepsilon}}\right)\sqrt{\left(\frac{\chi_{01}}{a}\right)^2 + \left(\frac{p\pi}{h}\right)^2} \quad (1)$$

The engine is illustrated in Figure 3. The cavity is partitioned in two halves separated by a dielectric, quartz plate. The propellant is swirl-injected tangentially in the nozzle side of the cavity (plasma chamber). This is done for both cooling of the chamber interior walls and for axial stability of the plasma. The other side near the antenna (upper chamber) is kept pressurized to ensure that the plasma formation takes place only in the plasma chamber where the propellant is fed in at lower pressure and brought slowly up to the desired chamber pressure. The engine's plasma chamber has two sets of injection holes, one pair near the separation plate and the other pair near the nozzle, to determine the effect of swirl port location on the stability of the plasma near the nozzle. The plasma is created by the region of high electromagnetic field strength formed at the center of the cavity near the nozzle. The propellant gas is heated by being forced to flow in close contact to the plasma as it expands through the nozzle converting thermal energy to directed kinetic energy, creating thrust.

An observation window is on the side of the thruster for viewing into the plasma chamber to verify plasma stability and location. The holes in the metal body for this viewing window (as well as the 0.25mm nozzle throat) are too small to allow a significant portion (less than 0.1% of incident power) of the microwave energy to exit the cavity. The body of engine is aluminum while the nozzle plate is stainless steel for greater survivability in the event that the plasma should briefly contact the nozzle plate. The test article is shown in Figure 4 below.

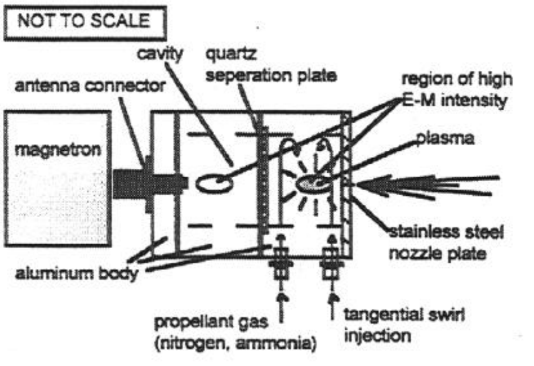

Fig. 3: Engine Schematic.

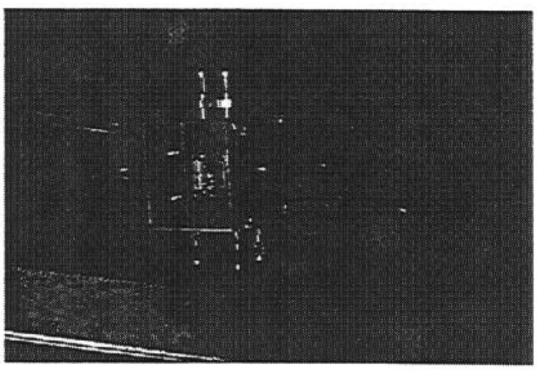

Fig. 4: Photo of Engine Test Article.

Test Facility

The experimental setup, shown in Figure 5, consisted of a propellant gas bottle supply attached to UNIT Instruments, UTS-8100, 750 sccm, digital mass-flow controller. The propellant lines feed into a vacuum facility which is capable of slightly less than 1 torr of pressure during operation of the thruster while operating with the Stokes mechanical pump only. The power-supply and microwave magnetron are also outside of the vacuum chamber. A secondary isolator is attached to the magnetron for greater safety against reflected power into the magnetron. A flexible microwave coaxial transmission cable is fed into the vacuum tank to attach to the engine's antenna connector.

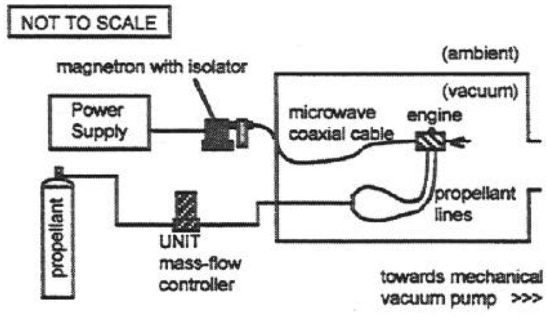

Fig. 5: Experimental setup.

A pendulum-based thrust stand was constructed to measure milliNewton range thrust levels. This thrust stand setup is illustrated in Figure 6. The engine is suspended from two pieces of 0.001" thick, stainless-steel shim stock. A displacement transducer measures the horizontal displacement of the system in inches as the thruster pushes against the gravitational restoration force in the pendulum. A force of 10 mN results in a typical displacement of 0.00485 inches.

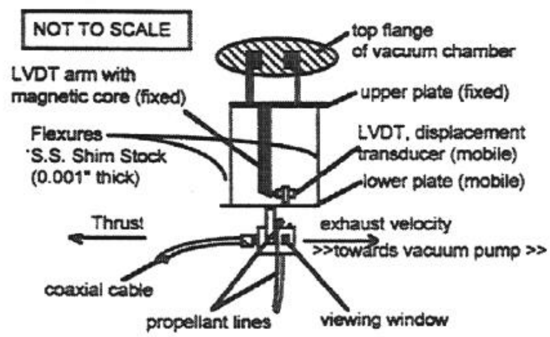

Fig. 6: Pendulum thrust stand

The initial goals of this program are to experimentally obtain values for thrust, specific impulse and thruster efficiency at low microwave power levels. Each of these values are obtained from mass flow and thrust measurements. Equations 2 and 3 show the formulas for computing specific impulse and overall thermodynamic efficiency. Mass flow measurements come from the UNIT mass flow controller with calibration traceable to NIST standards.

$$I_{sp} = \frac{\tau}{mg} \quad (2)$$

$$\eta_{overall} = \frac{\tau^2}{2 \cdot m \cdot P_{input}} \quad (3)$$

Weight is suspended from a thin cotton thread to accurately calibrate the pendulum thrust stand. This calibration is done with at least six different weights ranging from 1.3 to 3.4 grams, which translates to forces ranging from 12.5 to 33.4 mN. The calibration is done prior to each series of tests. Figure 7 shows typical calibration curves prior to cold-gas testing with helium and nitrogen. The two curves represent two different days of testing.

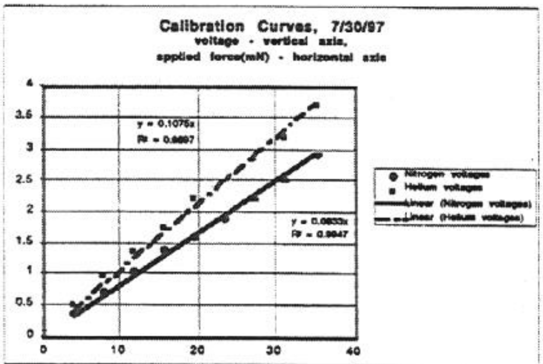

Figure 7: Thrust stand calibration.

Linear regression of the calibration data gives an equation to relate the differential voltage read from the transducer directly to thrust.

Results:

Cold flow data has been obtained for both helium and nitrogen. Tabulated cold flow results are below in Table 1. Ideal Isp values were calculated by CET (1993 version). Helium matches ideal values quite well, while nitrogen is slightly lower than expected. The results of the cold flow testing are very close to expected values. A photo of the thruster installed on the thrust stand for cold-gas testing is shown in Figure 8.

Sustained helium plasma was formed at ambient conditions with a chamber pressure of 5 kPa (gauge) and an incident power level of 20 Watts. The plasma was elliptical and correctly positioned near the nozzle along the cavity's longitudinal axis.

	Nitrogen	Helium
Thrust(mN)	6.568	3.562
mass flow (mg/sec)	17.864	4.428
Isp (sec)	37.48	82.01
Ideal Isp (sec)	42.30	82.40

Table 1: Cold flow results.

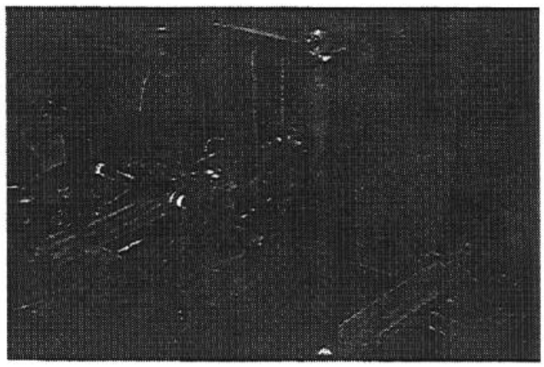

Figure 8: Photo of cold-gas testing.

Conclusions:

The microwave arcjet has advantages over conventional arcjets in use today. The electrodeless design eliminates cathode erosion problems associated with DC arcjet types. Due to the tangential swirl injection of the propellant for plasma stabilization, the limited chamber temperature associated with material aspects of resistojets is also increased due to the plasma's axial location and the cold propellant gas's injection from the wall. The 12,000 K plasma formed by the resonant microwave energy should offer high specific impulse at low incident power (~ 100 W). Thrust levels of 30 mN and specific impulse values near 500 seconds are expected for ammonia propellant. The microwave arcjet shows great promise for low thrust applications such as deep-space missions and geosynchronous North-South station-keeping.

Cold flow testing has been performed in ambient conditions with helium and nitrogen. Helium plasma has been ignited with 20 Watts of microwave power at 5 kPa (gauge) chamber pressure.

Future work for this project includes thrust stand measurements in vacuum. The work will include thrust, specific impulse, and thruster efficiency measurements for ammonia, nitrogen, helium, hydrogen and water vapor propellants exhausting into a vacuum.

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