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PERFORMANCE TESTING OF A FIXED CONFIGURATION MICROWAVE ARCJET THRUSTER

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SUMMARY

The microwave arcjet thruster uses microwave energy to create a free-floating plasma discharge within a microwave resonant cavity. This discharge typically absorbs 99% of the input power and converts it to thermal energy which is then transferred to the flowing propellant gas. Recent modifications have allowed the thruster to be operated in a fixed configuration where neither the cavity geometry nor the tuning mechanisms are adjusted. The prototype has demonstrate its ability to operate in this fixed configuration using a variety of propellant gases, i.e. nitrogen, helium, ammonia, and hydrogen. The current design is capable of efficient operation over a wide range of power levels (250 W to over 6000 W). Current work is focused on obtaining LIF velocimetry data of the velocity profile at the exit plane of the nozzle.

TECHNICAL DISCUSSION

This work is a continuation of an ongoing effort at Penn State to develop a prototype microwave powered satellite propulsion system. The device, which in previous papers has been referred to as a microwave resonant cavity electrothermal thruster, will for the sake of brevity be referred to as the microwave arcjet. The development work at Penn State has spanned most of the last decade and has entailed an extensive experimental effort which has been augmented by numerical simulations. Results of early studies have indicated that a design based upon a cylindrical cavity operating in the TM_{011} resonant mode would be best suited for thruster applications. A microwave arcjet of this type uses microwaves to form and maintain a plasma within the cavity; cold gas passes through the cavity, is heated by the plasma source, and passes out of the device through a nozzle to produce thrust.

The microwave arcjet is characterized by a free-floating ac plasma discharge. The location of the discharge, which forms at regions of maximum power density, is determined by the pattern of electric power density within the cavity. Proper cavity design produces patterns which result in an axially located plasma which is positioned directly upstream of a nozzle incorporated into one end of the cavity. Operation in this configuration has the net effect of producing a flow constriction be-

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tween the plasma discharge and the nozzle inlet. It is in this constricted region that the bulk of the heating process occurs. The microwave discharge typically resides very close to the nozzle inlet, which may cause erosion of the nozzle during high power operation. Therefore while some erosion may be a concern, the erosion is not of a critical electrical component as is the case with the conventional arcjet.

Work on the microwave resonant cavity design for thruster applications was initiated by Michigan State University [Ref. 1] in the early 1980's. This work was continued at Penn State by Balaam and Micci [Ref. 2], Mueller and Micci [Ref. 3], and Sullivan and Micci [Ref. 4]. These experimental studies quantified the plasma formation process, and the effectiveness of using the plasma discharge to heat a flowing propellant. The results of the experimental and numerical work [Ref. 5] at Penn State which were augmented by some preliminary high power work at NASA LeRC [Ref. 6], were used to develop a design of a first-generation microwave arcjet prototype. A full description of this device and the relevant theory have been presented in an earlier paper [Ref. 4] and will not be repeated here. The prototype was designed to remove many of the undesirable operational features of the earlier cavities. The design demonstrated that it could consistently produce stable discharges located in the desired position within the cavity at operating conditions up to 300 kPa and 2.2 kW. This design also demonstrated that it could be successfully operated using a variety of propellant gases, i.e., He, N_2, H_2, and NH_3. The initial work concentrated on qualifying the thruster performance in terms of vacuum I_{sp} as a function of specific power, where the vacuum I_{sp} was calculated using an ideal one-dimensional isentropic analysis. The results off this analysis yielded initial performance estimates for the prototype microwave arcjet. Representative values from this testing are given in Table 1.

Recent design modifications have been made which have allowed for improved performance of the microwave arcjet. A schematic of the modified device is shown in Figure 1. The main component of the prototype thruster is a resonant cavity which operates in the TM_{011} mode. The thruster is designed such that the plasma forms directly upstream of a graphite nozzle which is incorporated into the stationary short of the cavity. The formation of the plasma discharge near the inlet of the nozzle produces the most efficient transfer of thermal energy to the propellant gas.

The major modification of the thruster has been to make the resonant cavity a two section pressure vessel where the two sections are connected by a shunt line and cutoff valve. The two pressure sections are separated by a 0.635 cm thick boron-nitride plate. The incorporation of this plate was feasible because electric field pattern measurements which were conducted in previous experiments showed that a thin plate of boron-nitride placed at the mid-plane of a TM_{011} resonant cavity of these dimensions had only a minor effect on the overall resonant field pattern within the cavity. If the shunt valve is open, the pressure is equal in both chambers of the cavity and thus a pressure differential does not exist across the boron-nitride pressure plate. This configuration allows for high pressure operation without the risk of fracturing the pressure plate. The seal on the coaxial line is facilitated by a 0.635 cm thick teflon ring. If the shunt valve is closed the nozzle side of the cavity can be sealed and pumped down to a low pressure while maintaining an elevated pressure on the power inlet side of the cavity. This condition is used to cause the plasma to preferentially form within the low pressure side of the cavity in the desired location near the nozzle.

The second modification was to incorporate a full converging diverging nozzle into the prototype. The nozzle has an area ratio of 153 and is constructed of high density graphite. The conical nozzle has a 30 degree half-angle converging and a 15 degree half-angle diverging section. The diameter of the nozzle throat is 0.10 cm. The nozzle is located in the center of the stationary short, and because it is a conductor, it enhances the field density pattern on the axis of the cavity, thus insuring that the field pattern in the region of the nozzle closely resembles the ideal pattern. The microwave breakdown occurs in the vicinity of the nozzle and the plasma forms within the inlet of the nozzle; the plasma location is shown schematically in Figure 1.

The insertion depth of the coupling probe is adjustable, however, because of the pressure seals, adjustments cannot be performed during operation of the thruster. The device has to be disassembled in order to change the coupling probe insertion depth. The length of the resonant cavity of the prototype can also be changed by adjusting the position of a movable shorting plate, however, because of the nature of the pressure seals, the cavity length can also not be adjusted during actual thruster operation. Thus, for any given test, the geometry of the prototype design is fixed.

As stated earlier, the initial tests with the microwave arcjet prototype concentrated on qualifying the device's basic operating characteristics. These preliminary tests neither operated the thruster at the maximum powers or pressures available to the test facility, nor did they attempt to qualify whether or not the thruster could successfully be operated in a fixed configuration. The most recent testing has begun to examine both these aspects.

The modifications of the thruster have allowed for reliable operation of the thruster at pressures up to 500 kPa absolute. Previous testing could not exceed 300 kPa without risking damage to the boron-nitride pressure plate. At the time of this writing, higher pressure operation has not been explored, this is due solely to limitations of the gas feed system and does not reflect an operational limit of the microwave arcjet prototype.

The thruster has also been reliably operated at the maximum power output of the microwave generator. The nominal output of the generator is 2.2 kW. A complimentary experimental program which is using a cavity identical to the one described here has shown that the thruster can operate at power levels up to 6 kW [Ref. 7].

The primary goal of the current testing has been to demonstrate the fixed configuration operation of the microwave arcjet. It was identified early in the development stages of this prototype that fixed configuration operation was essential if this device was to be considered a viable satellite propulsion option. The requirement that the thruster geometry be varied between start-up and steady state operation would clearly be unacceptable for any feasible station keeping system.

The fixed configuration operation consists of fixing the cavity length, the position of the coupling probe and the adjustments of the three stub tuner. The plasma is then initiated in the nozzle side of the cavity at low pressure (~50 kPa) by the application of microwave power. Once initiated the plasma can be brought to operating conditions by increasing both power and mass flow rate. This type of operation has been demonstrated for both helium and nitrogen propellants. Typical performance data for these tests are given in Table 2 and Table 3. Using these propellants at input power levels of 2000 W the thruster has been continuously operated for periods up to 2.5 hrs.

Additional testing has demonstrated that both hydrogen and ammonia plasmas can be repeatable initiated at low pressures of 5-10 kPa within a fixed configuration system and that these plasmas can be brought to atmospheric pressures. While the work with these two gases has been limited in extent, work with ammonia has demonstrated that plasmas can repeatedly be operated at 300 kPa at 2200 W of input power with coupling efficiencies of 99%.

The current program is concentrating on determining the exhaust plume velocity profile at the exit plane of the nozzle using Laser Induced Fluorescence (LIF) velocimetry. The work in progress is concentrating on using this technique to determine the velocity profile of the thruster operating on nitrogen and exhausting into the ambient lab atmosphere. This work will either use the 654.48 nm band head of the 1st positive system, or a small amount of hydrogen will be used to seed the flow thus allowing the use of the 656.28 nm transition of the hydrogen atom.

Once this work has been completed the microwave arcjet will be mounted within the 1m x 1.5 m vacuum tank and extensive hydrogen and ammonia testing will commence. This work will include LIF velocimetry of the exhaust plume utilizing the 656.28 nm transition of atomic hydrogen. The data gained from these experiments will allow a qualitative comparison between the microwave arcjet and the hydrogen arcjet for which similar data has been obtained [Ref. 8].

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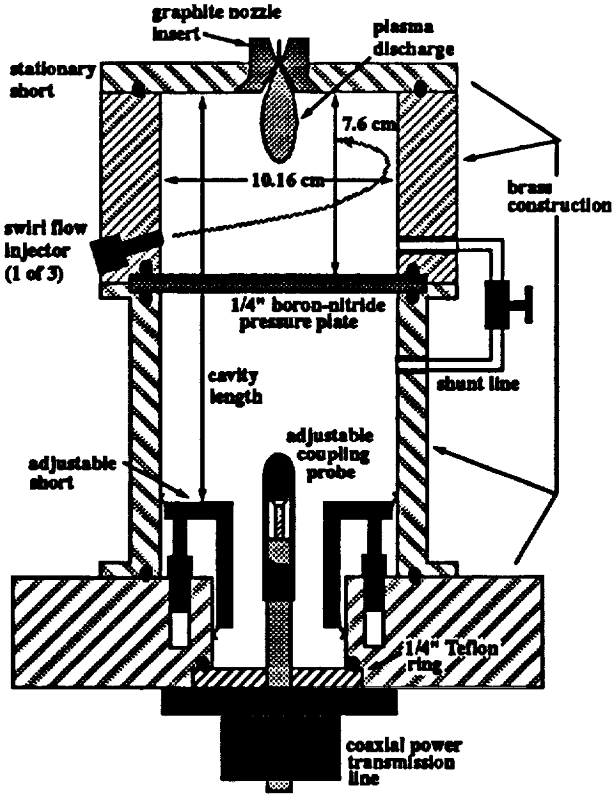

Figure 1: Schematic of the modified microwave arcjet prototype. The diameter of the cavity is 10.16 cm and the theoretical resonant length is 15.87 cm. While both the length of the cavity and the depth of the coupling probe can be adjusted, they must remain fixed during thruster operation. The entire cavity is divided into two pressure chambers which are connected by a shunt line and valve.

Table 1: Performance Estimates from Isentropic Analysis

Gas	Isp (s)	Specific Power (MJ/kg)	Thermal Efficiency
Helium	625	18	90%
Nitrogen	235	7	33%
Ammonia	425	18	55%
Hydrogen	1040	97	50%

Table 2: Nitrogen Performance Data

Incident Power (W)	Coupling Efficiency	Pressure (kPa abs)	Specific Power (MJ/kg)
1442	99%	433	4.21
1442	93%	358	5.05
1442	93%	328	5.51
1660	98%	407	6.31
1731	99%	408	6.43
1803	99%	448	6.35
1820	98%	478	4.12
2091	99%	498	4.31

Table 3: Helium Performance Data

Incident Power (W)	Coupling Efficiency	Pressure (kPa abs)	Specific Power (MJ/kg)
1442	98%	307	24.03
1658	98%	322	27.64
1803	98%	345	28.93
1803	98%	365	27.31
1947	98%	400	27.62
2236	99%	445	17.28