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Abstract
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 tests have demonstrated that the thruster can be operated in a fixed configuration where neither the cavity geometry nor the tuning mechanisms are adjusted. The prototype has demonstrated 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.

Introduction
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 comparable to a conventional arcjet in as much as they both heat the propellant gas in similar manners. Both these devices use electrical energy to generate high temperature plasmas which in turn heat a flowing propellant gas, but while similar, the two devices are actually quite different in their method of operation and the concerns which must be addressed for each thruster type when considering a design for a qualified flight system.

The arcjet, as its name implies, is characterized by a dc plasma arc which forms at the tip of a concentrically located cathode and terminates at an anode which forms the diverging section of the arcjet nozzle. Between cathode and anode, the arc passes through a constrictor section where the bulk of the heating process occurs. The heated gas then exits the device through the diverging nozzle. Three primary problems which arcjets have encountered have been arc formation, arc stability within the constrictor, and erosion of the cathode tip. The arc formation problem has been successfully addressed through the use of a sophisticated power processing scheme. The stability problem has also been solved by injecting the propellant gas into the thruster with a high degree of vorticity. The erosion problem, however, is inherent to the device; at present, flight ready hardware is designed such that propellant supply rather than cathode
erosion is the lifetime limiting factor. As mission complexity increases past that of satellite station-keeping, the overall importance of the effects of cathode erosion will become more critical.

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 above a nozzle incorporated into one end of the cavity. Operation in this configuration has the net effect of producing a flow constriction between 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 in the case with the conventional arcjet.

The power supply of a microwave thruster is a magnetron based microwave generator. Proper design will allow the generator to operate at a single power level. The technology required to produce such a power source is mature and very reliable for power levels from 100 W up to 5000 W; the typical microwave oven is an example of a very sturdy and reliable system operating in the 1000 W range at 2.45 GHz. It must be noted, however, that these systems are not space flight qualified. So while the exact method of power generation for the microwave arcjet has not been extensively addressed, initial studies indicate that it should be less complex and more reliable than that used by conventional arcjet systems. The microwave based system is also able to create its plasma discharge in a consistently reliable manner. The plasma formation process does not result in any erosion problems as is the case with the arcjet, and consequently the microwave arcjet does not require a soft-start procedure. The microwave arcjet can operate at a single power level and thus will not require any power processing to make the transition from plasma formation to a stable high power plasma.

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, 3], Mueller and Micci [Ref. 4], and Sullivan and Micci [Ref. 5]. These experimental studies qualified 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. 6] at Penn State which were augmented by some preliminary high power work at NASA LeRC [Ref. 7], 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. 8] 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, N2, H2, and NH3. The initial work concentrated on qualifying the thruster performance in terms of vacuum Isp as a function of specific power, where the vacuum Isp was calculated using an ideal one-dimensional isentropic analysis. The results of this analysis yielded initial performance estimates for the prototype microwave arcjet. Representative values from this testing are given in Table 1.

**Theory**

This thruster concept is based upon the concept of using electromagnetic energy to form a plasma discharge which in turn acts as a resistive load which absorbs the incident electromagnetic energy and dissipates it as thermal energy which is transferred to a flowing propellant gas. This type of discharge can typically be produced at microwave frequencies. It is common to refer to these types of plasmas as free-floating since they are located at regions of maximum electric field density within the interior of the cavity and do not have to be attached to a solid surface.

Gas breakdown will occur and the plasma discharge will be maintained when the production of newly

**Table 1: Performance Estimates from Isentropic Analysis**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Isp (s)</th>
<th>Specific Power (MJ/kg)</th>
<th>Thermal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>625</td>
<td>18</td>
<td>90%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>235</td>
<td>7</td>
<td>33%</td>
</tr>
<tr>
<td>Ammonia</td>
<td>425</td>
<td>18</td>
<td>55%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1040</td>
<td>97</td>
<td>50%</td>
</tr>
</tbody>
</table>
ionized particles barely exceeds the rate of their loss by all deionizing processes, including diffusion, recombination, and attachment. For most practical circumstances encountered in practice, a plasma can be maintained as long as the ratio of the electric field strength to the local gas pressure, i.e., \( E/p \), can be maintained high enough that ionization is ensured. This ratio primarily represents the amount of kinetic energy an electron can acquire before it experiences a collision.

The magnitude of the ratio required to produce and maintain a plasma discharge will vary between different gases. The easiest types of gases to breakdown are monatomic gases. In the case of the molecular gases, vibrational and rotational energy levels can absorb the kinetic energy transferred in the inelastic collision with an energetic electron. The presence of these internal energy levels reduces the probability that a given inelastic collision will result in either an excitation or an ionization of a molecule. This is because energy which is coupled into these internal levels does not act to increase the electronic energy level of the molecule. The practical result of this is that the more complex a molecule is the greater the ratio of \( E/p \) must be to induce breakdown and maintain the plasma discharge.

As stated the chosen mode of operation for the microwave arcjet prototype is the TM\(_{011}\) resonant mode. This mode is of interest for thruster applications because it is well suited for producing stable axial microwave plasma discharges. The field equations in cylindrical coordinates which describe this mode are given by

\[
E_z = E_{011} J_0\left(\frac{x_{01}a}{a}\right) \cos\left(\frac{\pi z}{h}\right) \quad (1)
\]

\[
E_\phi = 0 \quad (2)
\]

\[
E_\rho = E_{011} \frac{\pi a}{x_{01}a} J_1\left(\frac{x_{01}a}{a}\right) \sin\left(\frac{\pi z}{h}\right) \quad (3)
\]

The geometry of the cavity, i.e. its radius \( a \) and its resonant length \( h \), are dependent on the operating frequency. For the TM\(_{011}\) mode this relationship is:

\[
f_r = \frac{1}{2\pi \sqrt{\mu \epsilon}} \sqrt{(x_{01}/a)^2 + (\pi/h)^2} \quad (4)
\]

In the above equations, \( x_{01} \) is the first zero of the \( J_n \) Bessel function and has an approximate value of 2.405, \( \mu \) and \( \epsilon \) are the permeability and permittivity of the medium, respectively [Ref 9].

The power absorbed by the plasma is proportional to the electric power density which is equal to the square of the sum of the individual electric field components. Since equation (2) states that \( E_\phi = 0 \) for the TM\(_{011}\) mode, the electric power density is dependent upon \( E_\rho^2 \) and \( E_z^2 \) only, and the amount that each component contributes is determined by the geometry of the cavity. This geometry dependence is of the form

\[
(\pi a)^2 \left(\frac{x_{01}h}{a}\right)^2 = A \left(\frac{a}{h}\right)^2 \quad (5)
\]

which comes from the \( E_\rho^2 \) term; the constant terms have been collected into \( A \). For a cavity where \( a/h < 1 \), the \( E_\rho^2 \) term is very small and most of the electric power density within the cavity results from the \( E_z^2 \) term. For \( a/h = 1 \), the contributions from \( E_\rho^2 \) and \( E_z^2 \) are almost equal in magnitude, and as \( a/h > 1 \), \( E_\rho^2 \) becomes the dominant component. The thruster prototype has demonstrated that it is desirable to have a cavity where \( a/h < 1 \). This situation concentrates most of the field density on the axis of the cavity, thus creating an ideal situation for producing and maintaining a stable axial discharge which will be positioned near an axially located nozzle.

A resonant cavity with imperfectly conducting walls containing a lossy plasma, and the coupling mechanism which connects it to the transmission line, can together be considered as the terminating load which has a complex impedance, \( Z_L \). If this load impedance can be matched to the impedance of the transmission line, \( Z_0 \), then the maximum amount of power will be absorbed by the cavity/plasma system. This matching can be accomplished either by active coupling (i.e. varying the cavity geometry) or by the use of a multiple-stub tuner.

The previous work demonstrated that the thruster could be tuned to produce excellent power coupling at many different operating conditions. The active coupling consisted of varying both the insertion depth of the power coupling probe and the length of the cavity by adjustment of the position of a sliding short. These adjustments were made while the thruster was operating and could be iteratively adjusted to maximize power coupling at a particular operating condition of input power and propellant gas flow rate. Additional tuning utilized a commercial three-stub tuner which was placed in the microwave waveguide between the generator and the microwave arc-
Prototype Thruster Modifications

This section will describe the current design of the microwave arcjet. The design is very similar to that described in the previous paper [Ref. 7], however, some important modifications have been made which have allowed for improved performance. A schematic of the modified device is shown in Figure 1, and the current experimental set-up is shown in Figure 2. The main component of the prototype thruster is a resonant cavity which operates in the TM_{011} mode. As previously stated, this mode is optimal for producing an axial, free-floating plasma. 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 [Ref. 6].

The cavity geometry has been chosen to produce a value of a/h which is less than one. This concentrates the electric field density pattern within the cavity at the upstream and downstream axial regions. The cavity diameter of 10.16 cm was chosen to produce the desired electric field density distribution as well as to facilitate fabrication. The cavity is constructed of brass and its interior is kept highly polished to remove metal oxides to maintain a high electrical conductivity. The ideal resonant length for a cavity of this diameter as calculated by equation (4) is 15.87 cm which results in an a/h = 0.320.

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. Thus the cavity could be made into a two chamber pressure vessel without greatly distorting the ideal TM_{011} resonant mode, while at the same time isolating the axial high field region near the nozzle inlet from the high field region near the coupling probe.

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
Figure 2: Experimental configuration used in the testing of the microwave arcjet prototype.

nozzle is located in the center of the stationary short, and because it is constructed of 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.

Previous experiments demonstrated that the plasma location is also significantly affected by the position of the coupling probe [Ref. 2, 3, 5]. Specifically this work showed that asymmetric positioning of the coupling probe resulted in off-axis motion of the plasma discharge at high power operation. The coupling probe in the prototype is aligned along the cavity axis. This axisymmetric introduction of microwave power does not produce any off-axis field distortions. The lack of field distortions produced by the coupling probe and the better field density distribution of the prototype produce a plasma discharge which is very stable. The insertion depth of the coupling probe is adjustable, however, because of the pressure seals, adjustment 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.

The prototype incorporates three gas injection ports which produce a swirling gas flow which is directed down along the axis, i.e. toward the nozzle, at 15 degrees. The gas flow entering from each port is essentially tangential to the wall of the cavity. This swirling flow increases the axial stability of the plasma discharge and helps to insure that the discharge remains centered within the nozzle inlet.

Optical access of the plasma is made possible by a view port located in the wall of the pressure section of the cavity. The view port is formed from a circular pattern of 1.5 mm holes which have been machined into the cavity wall. The view port is approximately 3.2 cm in diameter. The dimensions of the holes do not allow microwave energy to be transmitted through them, and the close spaced pattern (98 holes in a 3.2 cm diameter) allow good visual access. The port is covered by a quartz window and incorporates an o-ring seal.

The microwave circuit (see Figure 2) consists of the microwave generator which can produce up to 2.2 kW of microwave power at a frequency of 2.45 GHz. The power from the generator is directed through a three-port circulator towards the cavity. A three-stub tuning device is placed in the transmission line just before the transition is made from the rectangular transmission line to the coaxial line which is terminated by the coupling probe. The three-stub tuner, as previously described, can be used in conjunction with the variable geometry of the cavity to produce an optimally matched condition between the transmission line and the cavity. Any power not absorbed by the plasma is reflected back towards the
Prototype Operation and Performance

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. Most of the work presented here deals with the operation of the thruster with nitrogen and helium propellants, however limited testing with both ammonia and hydrogen has also been conducted.

The modifications of the thruster have allowed for reliable operation of the thruster at high operating pressures on the order of 500 kPa absolute (~5 atm). 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. 10].

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 most recent testing with the modified thruster just described has verified this fixed configuration start-up for both nitrogen (diatomic) and helium (monatomic) propellants.

Nitrogen Testing

The development of the fixed configuration geometry began with experiments using the adjustable geometry cavity. During this testing, the thruster operation with nitrogen was examined and its behavior was characterized. From these tests, a configuration for high power (i.e. greater than 1000 W) operation was determined. This fixed configuration was determined to have a cavity length of 15.3 cm (0.47 cm less than the theoretical resonant length) and a coupling probe insertion depth of 1.2 cm.

This geometry was then fixed in the present modified thruster. The initial start-up sequence was as follows:

- Cavity was vacuum purged, filled with nitrogen to just above atmospheric pressure, and the shunt valve was closed isolating each pressure section.
- The nozzle was sealed, and a vacuum pump was used to reduce the pressure in the cavity section where the nozzle is located to 5-10 kPa. A slow nitrogen flow rate was also maintained so as to insure a constant low pressure nitrogen atmosphere.
- Power was then applied, typically up to 1000 W, and the tuning stubs on the three stub tuner were adjusted until a plasma formed.
- Power and pressure were carefully increased while constantly adjusting the tuning stubs for maximum power coupling.
- The nozzle seal was removed and the shunt valve was opened once the cavity pressure reached atmospheric.
- Power and pressure were then increased and stub tuning was continued until a desired operating condition was achieved.

Once this was accomplished, the system was then shut down. After a number of hours had elapsed, a fixed configuration start-up was then attempted and proved successful. The fixed configuration start-up is similar to the above except that the tuning stubs are not adjusted, and the plasma does not form until the operating power condition is reached. Once the plasma forms, the flow rate is increased until the identical operating condition is achieved. This fixed configuration start-up has proven to be both repeatable and reliable.

During high power, fixed configuration operation, it has been observed that the plasma will extend along the cavity axis from the nozzle inlet to the boron-nitride pressure plate. This plasma column forms as the pressure is increased from 5 kPa to approximately 200 kPa. A slight reduction in the input power level causes the plasma to contract to a compact plasma located within the
The fixed configuration consists of the cavity length, the probe insertion depth and the position of the tuning stubs. The tuning stub positions basically reflect the impedance of the microwave transmission line required to match the impedance of the plasma load at the given operating condition. Thus a three stub tuner would not be required for an actual thruster system, but rather the impedance of the power supply would be designed to match the plasma impedance at the desired operating condition. Testing has shown that each fixed configuration is proper for a single power level. Increasing or decreasing the power level away from this optimal value acts to reduce the overall power coupling to the plasma.

Some typical operating conditions for nitrogen are presented in Table 2.

**Helium Testing**

Testing with helium has yielded results which are similar to that of nitrogen. Helium plasmas can be both created and brought to a desired fully tuned operating condition using a system of fixed geometry. The one notable difference is that the plasma tends to form at lower power levels which are below the power level of the desired operating condition. This is most likely a result of the monatomic nature of helium which allows it to form plasmas more easily than polyatomic molecules. The formation of helium plasmas and the transition to high power high pressure operation using a fixed configuration prototype system has proved to be both repeatable and reliable.

One major difference between helium and nitrogen plasmas is that the helium plasma does not exhibit any tendency to extend the length of the cavity during high power operation. The plasma is very well behaved and always coalesces into a compact plasma located in the converging inlet of the nozzle.

Some typical operating conditions for helium using the modified thruster are presented in Table 3.

**Ammonia and Hydrogen**

A detailed study of the operation of the microwave arcjet using hydrogen and ammonia propellants has been limited due to the current configuration of the test facility. The tests which have been conducted with nitrogen and helium have allowed the nozzle to simply exhaust into the lab. Since the same procedure is not possible with either ammonia or hydrogen, the testing which has been conducted with these gases has surrounded the nozzle exhaust with a nitrogen purge and directed the exhaust into a venting system. The nitrogen purge is required because the exhaust will burn when it encounters the oxygen in the lab air. Tests of this nature, however, have been limited in their scope and extent due to safety concerns. More complete testing with these two gases will be conducted within our 1m x 1.5m vacuum tank facility in the upcoming months.

The limited 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. 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%.

One interesting characteristic of these plasmas is the intense heat transfer from the plasma to the cavity system. When operating with either helium or nitrogen, the heat transfer to the thruster is moderate compared to the heat transfer to the gas flowing through the nozzle. Indeed the wall temperature is only warm to the touch after operating a nitrogen plasma at 1500 W for 15 min-

### Table 2: Nitrogen Performance Data

<table>
<thead>
<tr>
<th>Incident Power (W)</th>
<th>Coupling Efficiency</th>
<th>Pressure (kPa abs)</th>
<th>Specific Power (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1442</td>
<td>99%</td>
<td>433</td>
<td>4.21</td>
</tr>
<tr>
<td>1442</td>
<td>93%</td>
<td>358</td>
<td>5.05</td>
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<tr>
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<td>93%</td>
<td>328</td>
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<td>98%</td>
<td>407</td>
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<td>448</td>
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<td>478</td>
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<td>2091</td>
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<td>498</td>
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### Table 3: Helium Performance Data

<table>
<thead>
<tr>
<th>Incident Power (W)</th>
<th>Coupling Efficiency</th>
<th>Pressure (kPa abs)</th>
<th>Specific Power (MJ/kg)</th>
</tr>
</thead>
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<td>1442</td>
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<td>307</td>
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<tr>
<td>1658</td>
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<td>322</td>
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<td>27.31</td>
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<td>1947</td>
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<td>400</td>
<td>27.62</td>
</tr>
<tr>
<td>2236</td>
<td>99%</td>
<td>445</td>
<td>17.28</td>
</tr>
</tbody>
</table>
utes. In contrast to this, when operating a hydrogen or ammonia plasma, the cavity temperature rapidly increases to very elevated temperatures. This phenomenon is believed to be linked to the rapid increase in the thermal conductivity of hydrogen in the range of 4000 K as a result of its dissociation. At 4000 K the thermal conductivity of hydrogen is an order of magnitude greater than either helium or nitrogen.

The practical result of this is that plasmas created from either hydrogen or ammonia are not as easily maintained as nitrogen or helium plasmas. The reason for this is that the energy transfer from the plasma is so rapid that the plasma has a tendency to expend more energy than it absorbs from the field and spontaneously extinguishes. The results of the limited experimental work seem to support this hypothesis. The current work in this area has thus been directed to increase the specific power at which these plasmas operate so as to maintain stable discharges. For example, the high pressure ammonia plasma mentioned above was operated at a specific power of 15 MJ/kg.

The plasmas have also shown evidence of a secondary arc within the interior of the primary discharge. The secondary arc is blue and very sharply defined such that it looks like a classic electric arc. The cause and nature of this secondary arc are unknown at this present time. However, no such similar behavior has ever been observed in the helium or nitrogen plasmas which have always appeared to be homogeneous.

LIF Velocimetry

The test program at Penn State has always been conducted in such a manner that continuous improvements in the thruster design have been compared to quantitative performance estimates. Up to this point, the only performance figures for the microwave arcjet have been estimates calculated from a one-dimensional isentropic analysis (for example see Table 1). The current program is concentrating on determining the exhaust plume velocity profile at the exit plane of the nozzle. This measurement will be made by a nonintrusive diagnostic method known as Laser Induced Fluorescence (LIF) velocimetry.

Laser induced fluorescence velocimetry is a diagnostic technique which has become more common in recent years as a nonintrusive way to measure the performance of electrothermal thrusters [Ref. 11, 12, 13, 14]. The technique measures the velocity of a single species within the plume and thus can only accurately resolve the mean velocity profile if the measured species is one of the major species in the exhaust plume. If the measured species is not a major component, then the measured velocity may not accurately represent the mean velocity distribution. However, this information is still useful for two reasons. The first is that the measurements provide a qualitative description of the exhaust plume; they can identify if the plume is symmetric about the plume axis, the manner in which the velocity decreases at points away from the center line, and the relative magnitude of the radial velocity component. The second reason is that it provides a baseline by which electrothermal thrusters can be compared.

Theory

Laser induced fluorescence velocimetry uses a tuned laser to excite a specific transition in an atom/molecule and the Doppler shift of the emitted light, i.e. the fluorescence, is measured. The measured Doppler shift can then be used to calculate the velocity of the atom/molecule. If light is emitted from a gas molecule/atom that is moving toward an observer or detector, the fluorescence signal will be shifted to a higher frequency, in other words the signal will have a shorter wavelength causing it to be blue-shifted. The change in frequency that the fluorescence signal will be Doppler shifted is given by:

$$\Delta v = \frac{v \cdot u}{c}$$  \hspace{1cm} (6)$$

This Doppler shift can be determined by making accurate measurements of the fluorescence signal from both a stationary (reference) source and the desired moving source. This measured Doppler shift can then be used to calculate the velocity at which the molecule/atom was moving toward the observer:

$$u = c \frac{\Delta v}{v}$$  \hspace{1cm} (7)$$

A general schematic of an LIF velocimetry experiment used to obtain both radial and axial velocity components in the exhaust plume is shown in Figure 3. The wave vector $k$ defines both the direction and magnitude of the fluorescence signal. The focusing lenses of the collection system can be translated radially, as indicated in the figure, to collect the shifted fluorescence signal at different radial locations. Two Doppler shifts $\Delta v_1$ and $\Delta v_2$ are determined by comparing these shifted signals to an unshifted reference fluorescence signal. The unshifted signal is ideally determined from the same experimental setup by using a third collection lens which is rotated 90 degrees out of the plane of Figure 3 such that
it is directed radially toward the nozzle and collects the fluorescence signal from the center-line of the nozzle plume. At this point the radial velocity should ideally be zero and the signal will be unshifted, this is shown schematically in Figure 4. The velocity components are then given by:

\[ u_x = \frac{\lambda (\Delta \nu_2 \sin \theta_1 + \Delta \nu_1 \sin \theta_2)}{\sin (\theta_1 + \theta_2)} \]  
\[ u_y = \frac{\lambda (\Delta \nu_1 \cos \theta_2 - \Delta \nu_2 \cos \theta_1)}{\sin (\theta_1 + \theta_2)} \]  

The technique as applied to electrothermal thrusters has primarily concentrated on resolving the velocity profile of the atomic hydrogen species within the exhaust plume. Using this technique the velocity profiles of plumes produced using both hydrogen and ammonia propellants have been successfully measured [Ref. 11, 12, 13, 14]. The technique which has been used by these other studies have used resonance fluorescence of the atomic hydrogen atom at 656.28 nm. At this wavelength, a velocity of 1000 m/s corresponds to a Doppler shift of 1.52 GHz and a velocity of 15,000 m/s corresponds to a shift of 22.86 GHz.

Current work

The work being conducted at Penn State with the microwave arcjet prototype is being directed at determining the velocity profiles for operation with ammonia, hydrogen and nitrogen. The LIF tests with either hydrogen and ammonia must occur within our vacuum facility. The LIF velocimetry with nitrogen has been initiated to see if preliminary information about the plume behavior of the microwave arcjet can be obtained without the added complication of making these LIF measurements within the vacuum tank.

At present, the work has concentrated on determining the best method of approaching these LIF measurements. While there is some limited work available on nitrogen LIF [Ref. 15, 16], the application for velocity measurements has never been attempted. Our initial approach has been to examine the emission spectrum of the nitrogen plasma. At present the 1st positive system of the nitrogen molecule (500 nm - 1000 nm) has been examined, the emission spectrum is very hard to interpret due to the closely spaced rotational lines of the band spectrum. Also the high pressure operation results in collisional redistribution of energy between levels and makes the interpretation of the spectrum very difficult. It was hoped that the band head located at 654.48 nm would be easily recognizable; this should be one of the most intense band heads [Ref 17], however because of the energy redistribution this single rotational-vibrational line is not easily recognized. Use of this line would allow the same laser system to be used for both nitrogen plasmas and ammonia and hydrogen plasmas.

A second option which has been considered is to look at using the 2nd positive system of the nitrogen atom (300 nm - 500 nm), specifically the band head at
337.13 nm. It is believed that the collisional redistribution of energy should not be as severe in this regime. However, the operation of LIF in the UV range introduces some additional experimental complexity. A third option which is currently being examined is to use hydrogen to seed the nitrogen flow so that the 656.23 nm hydrogen atom transition can be used.

**Experimental Configuration**

The laser system to be used as an excitation source is a Nd:YAG (Quanta-Ray DCR-11) pumped tunable dye laser (Spectra-Physics PDL-3) which will use DCM dye to access either the 656.28 nm wavelength of the Balmer $\alpha$ transition of the hydrogen atom or the 654.48 nm band head of the nitrogen molecule.

The shifted and reference fluorescence signals will be collected through a series of collection optics similar to those shown in Figures 3 and 4, however, the initial testing will concentrate on resolving only the axial velocity component of velocity. The fluorescence signal will first be passed through a scanning Fabry-Perot interferometer. The Fabry-Perot (Burleigh TL-15) has a 12 mm clear aperture and a free spectral range (FSR) which can be varied from 15 - 1,500 GHz by changing the nominal mirror spacing. The specifications for this device quote that over this range the typical resolution varies from 300 MHz - 30 GHz. The output from the Fabry-Perot interferometer will then be focused through the inlet slit of a Czerny-Turner spectrometer (SPEX 1870 0.5 m Spectrometer) which acts as a second filter which can access the wavelength of interest while rejecting light outside this region.

The half-width of the measured fluorescence excitation spectrum of the Balmer $\alpha$ transition has been measured experimentally to be 31.8 GHz [Ref. 18]. As stated above, the range of expected Doppler shifts are between 1.54 - 22.86 GHz. The free spectral range of the Fabry-Perot will be chosen to be approximately 100 GHz. This should insure that both the line and its expected shift can be scanned without overlapping orders. This FSR corresponds to a typical resolution of 2 GHz. This resolution should be able to resolve over almost the entire velocity range of interest, noting that the limits of resolution are of the same magnitude of the expected Doppler shift of the lower velocities. The error in the measurements will depend greatly on the signals themselves and the ability to accurately determine the location of the peaks. An initial estimate is that the error may approach ±1000 m/s. The quantification of this error estimate and a methodology to reduce the error to its smallest value is a primary task of this initial testing.

The output from the spectrometer will be converted to an electrical output by a photomultiplier tube which will then be processed by a PC based data acquisition system. The PMT (Hamamatsu - 1P28A) has a spectral response from 185 - 700 nm with a maximum response at 450 nm. The cathode quantum efficiency at 656 nm is approximately 0.8%. If this low PMT quantum efficiency detrimentally effects the ability to conduct the proposed tests, it may be necessary to obtain a red sensitized PMT with a better quantum efficiency (8 - 10%) in the region of interest.

**Conclusions and Future Work**

The microwave arcjet has been demonstrated to operate in a fixed configuration system for nitrogen, helium, ammonia, and hydrogen propellants. The current work has allowed high power (up to 2200 W) and high pressure (up to 500 kPa absolute) operation with a fixed configuration with both nitrogen (diatomic) and helium (monatomic) propellant gases. The high pressure work has been made possible by the modifications which have been made to the device. The work with hydrogen and ammonia has been limited due to experimental facility restraints. An operational concern has been raised concerning the plasma stability as a result of the high rate of thermal transfer due to the high thermal conductivity of the hydrogen at 5000 K.

The work in progress is concentrating on using LIF velocimetry to determine the velocity of the exhaust plume at the exit plane of the nozzle. This work is currently looking at the possibility of using this technique outside of a vacuum tank to obtain the velocity profile of the thruster operating on nitrogen propellant. 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.

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References


