The Effect of Molecular Propellants on the Performance of a Resonant Cavity Electrothermal Thruster

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Abstract

The current experimental work on the resonant cavity electrothermal thruster concept has concentrated on the formation and stabilization of molecular plasmas. The cavity operates in the TM011 mode and the molecular propellants which have been examined are N2, NH3, and H2. It has proved possible to form stable N2 plasmas from 100 kPa absolute to 300 kPa absolute over the power range of 500 W to 1000 W. Coupling efficiencies of up to 96% have been achieved. Performance parameters over this range indicate a potential Ip of 166 s, a thrust range of 500 W to 1000 W. Coupling efficiencies of and

The cavity operates in the TM011 mode and the molecular electrothermal thruster as a viable contender in the area of molecular plasmas. The gases for which results are being presented are nitrogen, ammonia, and hydrogen.

In addition, this paper includes both an overview of the theory upon which the resonant cavity thruster concept is based as well as a summary of the results of the previous experimental studies. As a final section, this paper also contains a limited discussion on the design considerations which must be addressed if this concept is ever to become a working electric propulsion device.

Introduction

The concept of using microwave power as the energy source for a low thrust, high specific impulse thruster has been the subject of an intense experimental investigation at The Pennsylvania State University. Development work on this concept both at Penn State and elsewhere has indicated that this thruster concept shows excellent promise towards becoming a competitive secondary propellant gases. The gases for which results are being presented are nitrogen, ammonia, and hydrogen.

This initial work has proved that the concept is feasible, and experimental values from these initial studies have shown that the current experimental system has an overall efficiency of 68.9% and is capable of operating at a maximum calculated specific impulse of 543 s. The thrust has also been calculated and the values range from 0.27-0.40 N.1

This paper details research which has been undertaken to further qualify the resonant cavity microwave electrothermal thruster as a viable contender in the area of low thrust electric propulsion. In particular, this paper presents the results of an experimental program which has examined the possibility of using a number of different propellant gases. The gases for which results are being presented are nitrogen, ammonia, and hydrogen.

In addition, this paper includes both an overview of the theory upon which the resonant cavity thruster concept is based as well as a summary of the results of the previous experimental studies. As a final section, this paper also contains a limited discussion on the design considerations which must be addressed if this concept is ever to become a working electric propulsion device.

Resonant Cavity Theory

The central component of the thruster system is the resonant cavity. A resonant cavity is a conducting enclosure in which electromagnetic energy can be confined. The simplest forms of resonant cavities are those which have either rectangular or cylindrical cross-sections. These cavities are simply closed sections of waveguides whose lengths are varied to achieve resonance. This resonance is achieved because the ends, or shorts, of the cavity are perpendicular to the direction of propagation of the microwaves (which is generally axial), and thus reflect any incoming waves. With a cavity of correct dimensions, the incident and reflected waves are constructively superimposed to form standing waves of electromagnetic energy within the cavity. These standing waves form regions of intense AC electric fields which in turn act to initiate gas breakdown and plasma formation.

The electromagnetic fields propagating in a waveguide are governed by Maxwell’s equations which, when written in time-dependent form, constitute a hyperbolic equation set describing waves travelling at the velocity of light. Since resonant cavities are simply closed sections of waveguide, they must also be governed by

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Maxwell's equations subject to the correct set of boundary conditions. These boundary conditions arise from the condition that at the metallic waveguide walls only tangential components of the magnetic field and normal components of the electric field can exist. The two possible modes of propagation for the electromagnetic waves in a hollow, single conductor waveguide are the transverse magnetic (TM), and the transverse electric (TE). Note, the coordinate system which will be used for the following discussions is a cylindrical coordinate system which has its z-coordinate parallel to the direction of propagation of the electromagnetic wave.

The TE modes are characterized by a purely transverse electric field and a magnetic field with a non-zero component in the direction of wave propagation. Thus the boundary conditions which are imposed on the walls of the resonant cavity for the TE mode of transmission require that the following condition must be true

$$\frac{\partial H_z}{\partial n} = 0$$  \hspace{1cm} (1)

whereas at the ends of the cavity which are perpendicular to the direction of wave propagation it follows that

$$H_z = 0.$$  \hspace{1cm} (2)

The TM modes exhibit a purely transverse magnetic field and an electric field with a non-zero component in the direction of propagation. In this case the boundary conditions require that

$$E_z = 0$$  \hspace{1cm} (3)

at the side walls of the resonant cavity, whereas at the ends of the cavity, which are perpendicular to the direction of wave propagation, the boundary conditions require that

$$E_\theta = 0...and...E_r = 0.$$  \hspace{1cm} (4)

The resonant cavity device under consideration operates in the TM mode of transmission and is of circular cross section with its geometry is defined in terms of radius, $b$, and a length, $l$.

Applying the boundary conditions which apply to the TM mode to the form of Maxwell's equations which govern the propagation of electromagnetic waves in free space results in the development of the following set of equations describing the electric field components present in a resonant cavity operating in the TM mode.

$$E_r = -E_{\text{amp}} \left( \frac{p \pi b}{\rho_{\text{amp}}} \right) J_n \left( \frac{p \rho_{\text{amp}} r}{b} \right) \cos \left( n \theta \right) \sin \left( \frac{p \pi z}{l} \right) e^{iat}$$  \hspace{1cm} (5)

$$E_\theta = E_{\text{amp}} \left( \frac{p \pi b^2}{\mu \rho_{\text{amp}}} \right) J_n \left( \frac{p \rho_{\text{amp}} r}{b} \right) \sin \left( n \theta \right) \sin \left( \frac{p \pi z}{l} \right) e^{iat}$$  \hspace{1cm} (6)

$$E_z = E_{\text{amp}} J_n \left( \frac{p \rho_{\text{amp}} r}{b} \right) \cos \left( n \theta \right) \cos \left( \frac{p \pi z}{l} \right) e^{iat}$$  \hspace{1cm} (7)

The subscripts $n,m$, and $p$ are integers (0,1,2,3...) used to identify the various resonant conditions of a cavity operating in the transverse magnetic mode; using this notation a particular resonant mode is denoted as TM$_{nmp}$. In this system, $n$ represents the number of complete cycles of field variation in the azimuthal direction for $0 \leq \theta \leq 2\pi$, $m$ represents the number of half cycles of field variation in the radial direction for $0 \leq r \leq b$, and $p$ is the number of half cycles of field variation in the direction of propagation along the cavity axis for $0 \leq z \leq l$. These integer values describe different possible resonant conditions of the TM mode, a particular resonant condition of the transverse magnetic mode is denoted as TM$_{nmp}$. Finally, the term $\rho_{\text{amp}}$, not to be confused with the integer $p$, is used to represent the zero of the Bessel function.$^4$

Since there is, in general, more than one component of the electric field at any given point in the cavity it is usually more worthwhile to consider the magnitude of the total electric field vector when one is interested in the determining the locations of maximum electric field intensity within the cavity. The total electric field vector is defined as:

$$E^2(r,z) = E_r^2(r,z) + E_\theta^2(r,z) + E_z^2(r,z)$$  \hspace{1cm} (8)

The geometry of the resonant cavity is dependent upon both the microwave frequency and the operating resonant mode of the cavity. For a cavity which is resonant in the TM mode the governing equation describing its geometrical dimensions is as follows:

$$f_r = \frac{c_e}{2} \left[ \frac{p_{\text{amp}}^2}{(n \pi b)^2} + \frac{p^2}{r^2} \right]^{1/2}$$  \hspace{1cm} (9)

Where $c_e = 1 / (\sqrt{\mu \varepsilon})$ is the velocity of the electromagnetic wave in the dielectric medium filling the waveguide.

By using equation (8), it can be determined that the ideal resonance wave patterns developed by the TM$_{01p}$ modes exhibit centrally located, axially symmetric regions of peak electric field intensity; contour plots of the electric
field intensities for the TM_{011} and TM_{012} are shown in Figure 1. These contour plots indicate that in the ideal case each of these modes contain electric field maxima which lie along the central axis of the cavity; the TM_{011} mode has two maxima located on the cavity axis, one which is located at the top of the cavity and the other which is located at the bottom of the cavity. The TM_{012} mode also has maxima at the top and bottom of the cavity plus an additional maximum in the center of the cavity.

It is in these regions of maximum electric field that it is possible for energy to be transferred from the high frequency field to a gas through collisions between electrons and the neutral particles that form the major component of the gas. Electrons gain kinetic energy by being accelerated through the electromagnetic field. If the electric field is strong enough and/or the mean free path of the electrons is long enough, the electrons can gain enough energy so that their collisions with the neutrals in the gas are inelastic. When an electron and a neutral collide inelastically, there is a change in the internal state of the neutral at the expense of the kinetic energy of the electron. The change may involve an excitation of the neutral to one of its characteristic states, or single or multiple ionization may take place. If ionization does indeed take place and the situation is favorable, these new electrons may in turn produce ionization of other neutrals in the region. If this situation propagates a phenomenon referred to as cascade breakdown can occur and a plasma will form in the high field region.

**Dielectric Materials in a Resonant Cavity**

When a dielectric substance is placed within a microwave resonant cavity, the resonant length of the cavity will be altered. The reason for this behavior can be understood by remembering that the speed of propagation of the electromagnetic wave, $c$, is inversely proportional to the permittivity of the cavity which is defined as:

$$\varepsilon = \varepsilon_e \varepsilon_r$$

where $\varepsilon_e$ is the permittivity of free space and $\varepsilon_r$ is the dielectric constant of a given material. Considering the ideal situation in which the cavity is completely empty, the permittivity of the cavity is exactly equal to the free space value and the propagation velocity of the wave is identical to the speed of light in vacuum, or $3 \times 10^8$ m/s.

If, however, the cavity is filled with a material which has a dielectric constant which is greater than unity, the propagation velocity will be greatly reduced. For instance, filling a cavity with a substance having a dielectric constant of four would reduce the propagation velocity by half. Equation (9) shows that a reduction in propagation velocity will result in a reduction in the resonant length of the cavity.

**When a cavity is completely filled with a dielectric, equation (9) can be used to calculate the new resonant length. If the cavity is only partially filled with one or more dielectrics and/or the dielectrics have complicated geometry, the calculation of the actual resonant length is not a straightforward procedure and simple analytical methods are not appropriate. In these situations it is usually easier to determine the resonant length of the cavity experimentally.**

The introduction of a dielectric material into a resonant cavity system has other effects besides altering the resonant length. The introduction of dielectric material, under certain conditions, can produce a loss mechanism within the system. The mechanism by which this may occur is dependent upon both the specific properties of the material and the frequency of the applied field and is explained as follows.

If a dielectric subject to a time varying electromagnetic field has a permittivity which is sufficiently low to permit its permanent and induced dipoles to follow the field variations without any measurable lag, the permittivity of the dielectric can be represented by its static value. If this condition is met the dielectric material does not absorb any energy from the oscillating electric field. This can be demonstrated by considering the relationship between the dielectric displacement density and the time varying electric field intensity:

$$D = \varepsilon_e \varepsilon_r E = \varepsilon_e \varepsilon_r E \cos \omega t = Re \{ \varepsilon_e \varepsilon_r E e^{j\omega t} \}$$

The displacement or charging density is then by definition:

$$J_d = \frac{dD}{dt} = Re \{ \varepsilon_e \varepsilon_r j\omega E e^{j\omega t} \} = -\varepsilon_e \varepsilon_r \omega E \sin \omega t$$

Thus it can be seen, that the current density leads the electric field intensity by a temporal phase angle of $\pi/2$.

The energy absorbed per unit volume of the dielectric material per second is defined as the energy density and is given by:

$$u = \frac{\omega}{2\pi} \int_0^{2\pi} J_d E dt$$

By substituting in the value of the displacement density the energy density within the dielectric as a result of being placed in the oscillating field is:
Thus it can be seen that under these conditions the dielectric does not absorb any energy from the field.

Now, however, if the frequency of the time varying electric field is sufficiently high such that the polarization of the dielectric becomes frequency dependent, the permittivity of the dielectric becomes complex such that the dielectric constant is expressed as:

$$\tilde{\varepsilon}_r = \varepsilon'_r - i\varepsilon''_r$$  \hspace{1cm} (15)

Through substitution it can be shown that this complex permittivity results in a current density such that:

$$J_d = -\varepsilon'_0 \varepsilon_r' \omega E_o \sin \omega t + \varepsilon''_r \omega E_o \cos \omega t$$  \hspace{1cm} (16)

The displacement current now consists of two parts. The first part is identical to the no loss case and does not lead to any energy absorption. The second term, however, which is associated with \(\varepsilon''_r\), is in phase with the applied field, and the corresponding energy density is thus given as:

$$u = \frac{\omega}{2\pi} \int_0^\infty \varepsilon'_0 \varepsilon_r' \omega E_o^2 \cos^2 \omega t \, dt = \frac{1}{2} \omega \varepsilon'_0 \varepsilon_r^2$$  \hspace{1cm} (17)

This development demonstrates that dielectric substance can absorb energy from a high frequency field which shows up as heat energy within the dielectric. The energy density which is absorbed by the dielectric is proportional to the term \(\varepsilon''_r\), which is termed the loss factor of the dielectric. This loss factor is not a constant, but rather is a function of the applied frequency, and the variation of the loss factor with applied frequency gives the absorption characteristic of the dielectric. In practice, it is convenient to specify the absorption loss in a dielectric in terms of a quantity known as a loss tangent which is defined as:

$$\tan \delta = \frac{\varepsilon''_r}{\varepsilon'_r}$$  \hspace{1cm} (18)

where \(\delta\) is defined as the angle between the total displacement current, \(J_d\), and its lossless component.

Microwave frequencies are high enough that most dielectrics will exhibit a complex permittivity. Thus, in general, the dielectrics with the smallest loss tangents are the most applicable for use within a resonant cavity. Materials which exhibit negligible dielectric losses in microwave fields have loss tangents which are of the order 0.0001.5

**Experimental Setup**

The resonant cavity which has been used in the experimental program at Penn State has been used primarily to investigate the TM\(_{011}\), and the TM\(_{012}\) modes. The diameter of the cavity is 17.78 cm and the length of the cavity is variable. The cavity has openings which are approximately 2.5 cm in diameter located in the centers of both the upper and lower plates. Microwave energy at a frequency of 2.45 GHz is introduced into the cavity by means of a a 16.6 mm diameter coupling probe which enters the side of the cavity through one of two coupling ports which have been designed into the cavity for this purpose; the coupling probe is essentially the central conductor of a coaxial waveguide. The coupling port used by the coupling probe contains an compressed air line which is used to cool the interior of the cavity during test runs. The cavity also contains a viewing widow which is serenade by a fine copper mesh. The microwave energy is unable to escape from the cavity to the surroundings through these holes because the electric field lines are perpendicular to the cavity walls at these locations, as per the requirements of the boundary conditions which describe the TM mode of transmission. Each of these openings in the walls of the cavity represents a departure from the ideal cavity which was described in the previous section. It is thus somewhat reasonable to expect some departure from the ideal electric field patterns which are shown in Figure 1.

Given the diameter of the cavity, 17.78 cm, and the operating frequency, 2.45 GHz, equation (9) can be used to determine the theoretical resonant lengths of the cavity for both the TM\(_{011}\) and the TM\(_{012}\) modes. The value of the corresponding Bessel function zero, \(p_{01}\), is 2.504. For the TM\(_{012}\) mode the value of the integer \(p\) is 2 and the ideal length of the cavity is determined to be 10.36 cm. The integer \(p\) takes a value of 1 for the TM\(_{011}\) mode, and the length of the cavity necessary to excite this mode of operation is 7.21 cm.

In order to insure that the plasma discharge formed at one of the central axis maximums, the gas flow systems used in these experiments utilized quartz pressure vessels which were placed inside the cavity and aligned along its central axis. The dielectric loss tangent of the fused quartz used to construct this pressure vessel is 0.0002; the experiments which have been conducted give no indication that any microwave power is absorbed by the quartz vessel. The gas flow systems have been able to provide a countable flow of propellant gas through these quartz vessels at pressures which range from -100 kPa gauge up to 300 kPa gauge. The mass flow rate through the system is measured using an Omega FL-223.
The microwave power has been supplied by a Getling GL131A low-ripple, variable power magnetron, which is capable of generating powers up to 2.5 kW at a frequency of approximately 2.45 GHz. A rectangular waveguide transmits the microwave energy from the magnetron to a three port circulator which channels any reflected microwave power to a dummy load; this is necessary so as to prevent damage to the magnetron. Connected to the circulator is a 2-port directional coupler which in turn is connected to two thermistor power sensors which are used to monitor and measure the values of both forward and reflected power. The thermistors are connected to compatible analog power meters. A rectangular to coaxial waveguide transition is employed to convert the microwave power from the rectangular propagation mode to a coaxial propagation mode for introduction into the cavity.

**Operation in the TM\textsubscript{012} and TM\textsubscript{011} Modes**

**TM\textsubscript{012} Experimental Investigation**

The series of experiments which investigated the TM\textsubscript{012} mode were conducted to qualify the concept of the microwave resonant thruster.\textsuperscript{7,8} These experiments established that a stable free floating microwave plasma could be initiated within the resonant cavity. These experiments utilized a quartz vessel which was essentially a sphere, 10.2 cm in diameter, with two 20 mm inside diameter cylindrical tubes at its top and bottom to connect it to the rest of the gas system which was contained outside the cavity. Since the resonant length of the cavity in this mode was 10.36 cm, the quartz vessel provided an open region about the cavity's central axis in which the plasma could form and be free-floating.

The method of igniting a plasma was quite easy and very repeatable. The quartz tube was filled with the desired test gas, either helium or nitrogen and the pressure in the vessel was reduced to approximately -95 kPa gauge. The reduction in pressure serves to increase the mean free path of the electrons in the gas and thus aids in the process of cascade breakdown. Once the pressure had been reduced, the application of approximately 100 W of microwave power would cause a plasma discharge to form; the formation of the plasma was quite instantaneous, and once established, the plasma sat stably in the center of the quartz sphere at a location which corresponded to the central maxima of the TM\textsubscript{012} mode.

The results of this investigation, which have been more fully presented in previous papers, indicated that while it was possible to ignite both helium and nitrogen plasmas which where free-floating, the plasmas became unstable if the coupling efficiency was greater than 79%; the coupling efficiency is defined as the ratio of forward power into the cavity to the reflected power out of the cavity. This situation limited the forward power to 500 W. Above this power, the plasma was observed to move towards the walls of the quartz sphere causing them to heat very rapidly.

The results for helium showed that plasmas could be easily initiated at a pressures which were below atmospheric, and that these plasmas would remain stable as both the pressure in the quartz vessel and flow rate of helium through the vessel were increased; data for these experiments showed that, for an input power of 400 W, it was possible to maintain a stable helium plasma at a pressure of 300 kPa absolute and a flow rate of 0.463 g/s. These studies also verified that the transfer of thermal energy from the plasma to the flowing gas increased as the flow rate increased. The experimental results for free-floating nitrogen plasmas were quite different from those of the helium plasmas. Nitrogen plasmas proved to be considerably more difficult to ignite, but with some effort it proved possible to initiate a nitrogen plasma at gas pressures of -95 kPa gauge. The nitrogen plasmas proved to be stable at these low pressures, however, if the pressure in the cavity was increased above -60 kPa gauge the plasma would suddenly extinguish.

One of the most probable explanations for the difference in behavior observed between the helium and nitrogen plasmas is related to the fact that while helium is a monatomic atom, nitrogen is a diatomic molecule. The helium atom has few modes of internal energy storage; because of this, inelastic collisions with high energy electrons are highly effective in liberating free electrons and creating helium ions. On the other hand, the diatomic nitrogen molecule has a relatively large number of internal modes of energy storage when compared with the helium atom. The result of this is that the nitrogen molecule is much harder to ionize. Inelastic collisions that would ionize a helium atom may act to only simply excite an inner vibrational mode of the nitrogen molecule. This reasoning explains the increased difficulty in igniting the nitrogen plasma. By extending this reasoning, the plasma extinction at high pressures can be explained. Increasing the pressure in the quartz vessel acts to reduce the mean free path of the electrons thus reducing the available energy which can be transferred in inelastic collisions; thus reducing the number of free electrons and nitrogen ions which are produced. While at the same time, the increase in pressure promotes the recombination of the nitrogen ions and free electrons thus acting to deplete the plasma. At a given input power, a threshold pressure is reached at which the rate of ion-electron recombination exceeds the rate at which ions are produced by ionization and the plasma extinguishes. Under this reasoning, it would ap-
pear that if the input power could be increased, the nitrogen plasmas could be maintained at higher pressures.

**TM\textsubscript{011} Initial Investigation**

Before discussing the current work which has been conducted with molecular propellants, it is instructive to summarize the major findings of the initial TM\textsubscript{011} investigation with helium. A more detailed account of this phase of the TM\textsubscript{011} investigation is included in a companion paper.\textsuperscript{1} The motivation for changing the mode from TM\textsubscript{012} to TM\textsubscript{011} was to reduce the size of the cavity. With the cavity’s diameter fixed at 17.78 cm the length of the cavity reduces from 10.36 cm to 7.21 cm, a reduction of 30%. This length reduction becomes more pronounced as the diameter of the cavity is varied; for instance, the length of a cavity of diameter 10 cm reduces from 35.1 cm to 17.6 cm, a reduction of 50%.

The move to the TM\textsubscript{011} mode also incorporated two major improvements over the TM\textsubscript{012} investigation. The quartz pressure vessel was modified so as to allow for a free floating plasma while at the same time incorporating an orifice plate which provided a means of estimating the device’s potential \textit{I}_\text{sp}. The second improvement was the introduction of a stabilization device which was used to hold the plasma in place on the cavity axis using fluid dynamic effects.

Both the orifice plate and the stabilization device were constructed of the ceramic boron-nitride. Boron-nitride has a dielectric constant of 4.8, a loss tangent of 0.0004, and is able to withstand temperatures up to 3000 K.\textsuperscript{9}

Investigation of stabilization techniques indicated that either a bluff body, similar to theory in a combustion system’s flame holder, or a flow swirler, such as are used with arcjets, would provide adequate stabilization to the plasma. The helium studies validated the effectiveness of the bluff body technique, but was inconclusive in qualifying the usefulness of the flow swirler.

The bluff body was placed inside the straight tube section of the modified quartz pressure vessel, and its position could be varied along the axis of the cavity. The allowed the bluff body’s base to be located on the axis directly upstream of either of the two axial maxima. The quartz tube with the bluff body inserted and the orifice plate attached is shown in Figure 2. The diameter of the orifice in the plate is 1.0 mm, and the plate was affixed to the quartz using a low loss tangent, high temperature silicone gasket sealant. A major disadvantage of this configuration is that the bulk of the orifice plate is located in the same volume of space which contains the theoretical location of the lower E-field maximum; compare Figure 1 with Figure 2.

The potential \textit{I}_\text{sp} is calculated using isentropic flow theory. The stagnation temperature within the cavity, \( T_o \), can be calculated using

\[
\dot{m} = \frac{AP_o}{\sqrt{RT_{oh}}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}
\]  

Here \( \dot{m} \) and \( P_o \) are the mass flow rate of the gas and the cavity pressure; both of which are measured quantities, and \( A \) is the known area of the choked orifice. For helium (\( \gamma = 1.666 \)) a pressure ratio of 2.05 must be maintained for choked flow. Once the stagnation temperature within the cavity is determined, the potential \textit{I}_\text{sp} of the device assuming an ideal expansion to vacuum can be calculated from

\[
I_{sp} = \frac{\sqrt{2C_pT_o}}{g}
\]

and likewise the ideal thrust can be calculated using

\[
T_f = \dot{m}I_{sp}g
\]

The system efficiency may also be calculated using the measured values of system pressure and mass flow rate and the calculated value of stagnation temperature by using:

\[
\eta = \frac{\dot{m}c_p}{P} (T_o - T_{oc})
\]

where \( T_{oc} \) is the stagnation temperature of the cold gas upsweep of the plasma, and \( P \) is the measured incident microwave power.

The helium plasmas were produced in the same manner as that used for the TM\textsubscript{012} mode, except in this case the bluff body was present. Two different types of plasma formation were observed, and they differed solely on the position of the bluff body.

When the bluff body base was positioned even with the sliding short, the helium plasma would consistently form in the location of the upper node. Once the plasma was formed the cavity could be tuned such that it was close to being matched to the coaxial transmission line. This close matching resulted in coupling efficiencies which were 97% or greater for most test runs. Thus the bluff body stabilization results in almost a 20% increase in coupling efficiency over that of the free floating plasma investigated in the TM\textsubscript{012} mode.

At pressures below atmospheric, the plasma
appeared as a diffuse glowing cloud which tended to fill most of the quartz vessel; the plasma glow was most intense at a location which corresponded to the upper maximum. As the pressure and power were increased the plasma cloud contracted, brightened and did not exhibit any tendency to move off the cavity axis. During these tests it was also observed that the plasma was in contact with the bluff body.

By using this stabilization technique it was shown that the upper node ignition of a helium plasma was straightforward and highly repeatable. It was further demonstrated that it was possible to maintain a stable axial plasma at input powers of 2.25 kW, pressures of up to 200 kPa, and coupling efficiencies of greater than 97%. This method of operation resulted in a maximum $I_p$ of 543 s and a maximum thrust of 0.4 N.\textsuperscript{1}

If the plasma forms in a location closer to the nozzle, the overall heat transfer to the propellant gas should theoretically increase.\textsuperscript{10} In order to take advantage of this situation, the bluff body was positioned further into the cavity. This new position placed the base of the bluff body above the theoretical location of the upper node, i.e. above the location of the orifice. Since in this configuration the bluff body also occupies the same volume of space as the upper node, a plasma was prevented from forming in this location.

This configuration resulted in the plasma forming at the bottom of the cavity. However, the plasma did not form on the axis, but rather formed at a location that placed it in contact with both the boron-nitride orifice plate and the quartz wall. This location does not correspond to a maximum in E-field strength, and thus the formation of the plasma at that position was not expected. This behavior may be the result of perturbations in the ideal electric field configuration caused by the asymmetric position of the coupling probe.

To summarize the major findings of the TM\textsubscript{011} helium research, it was found that fluid dynamic stabilization techniques provided an adequate means of plasma stabilization. It showed that boron-nitride was an effective and durable material for microwave thruster applications, and finally it demonstrated that it was possible to maintain a stable helium plasma at 2.25 kW and 300 kPa absolute while achieving coupling efficiencies of 97% plus.

**TM\textsubscript{011} Current Experimental Investigation**

The current experimental work on the development of the microwave electrothermal thruster has concentrated on examining the possibility of using molecular gases as propellants. The following section details the results of experiments with nitrogen, anhydrous ammonia, and hydrogen.

The same test rig as used for the helium test was used for the molecular propellant experiments. The only modifications were to invert the cavity so that the exhaust from the orifice is directed up into a fume hood, and to provide for the simultaneous flow of two gases, one being helium and the other being one of the three molecular propellants through the pressure vessel. A schematic of the test rig is shown in Figure 3.

Two different methods of plasma ignition have been tried. The first method has been used for all three gases and has had varying amounts of success. This method involves the transition from a stable helium plasma to a molecular plasma. In both cases a helium plasma is first ignited in the same manner as used in the initial TM\textsubscript{011} investigations. Once the plasma has formed, a transition to a molecular plasma is then attempted by slowly decreasing the helium flow while simultaneously increasing the flow of the molecular propellant. The second method of ignition which has been used for the hydrogen studies involves the introduction of a tungsten wire into the high field region of the cavity. This procedure results in the emission of highly energetic electrons which act to promote cascade breakdown. This process has been used previously to initiate the formation of helium plasmas at atmospheric pressures.\textsuperscript{11}

The above describes the three methods which have been utilized to form plasmas from nitrogen, ammonia, and hydrogen at atmospheric pressures. The reasons which have led to this method of plasma formation are that the vacuum line is not capable of pumping either NH\textsubscript{3} or H\textsubscript{2}, and that it has proved impossible to spontaneously form plasmas from these gases at atmospheric pressures.

**Nitrogen Plasmas**

The motivation behind using nitrogen as a propellant gas is that even though its molecular weight is relatively high, it is easily stored, readily available, non-flammable, and non-caustic. The molecule, however, is diatomic and thus, it was expected that it would be more difficult to form a plasma due to the additional modes of internal energy storage.

It was found that with considerable practice, a nitrogen plasma could be formed using the first method described above. The following discussion and numerical results all correspond to nitrogen plasmas formed in this manner.

For these runs it was determined that for a cavity length of 6.65 cm, the helium plasma would consistently form behind the bluff body at the location of the upper node once the pressure was reduced to -95 kPa...
gauge and 700 W of forward power was supplied. The coupling probe position was such that its tip extended into the cavity a distance 0.312 cm. Once the plasma had formed the reflected power from the cavity could be reduced by increasing the cavity length to 6.73 cm and increasing the coupling probe depth to 2.55 cm. Under these conditions the coupling efficiency was greater than 97%. Since the theoretical resonant length of the cavity operating in this mode is 7.21 cm, it can be inferred that the presence of the quartz and boron-nitride dielectrics and the helium plasma act to reduce the resonant length by 0.48 cm.

Once the cavity is properly tuned the pressure within the quartz tube can be increased to atmospheric pressure. During this process the plasma transitions from a diffuse glowing cloud to a much more compact plasma column which is pink-white in color. The plasma can also be observed to be in direct contact with the bluff body. The introduction of a small flow rate of N₂ immediately changes the color of the plasma to a pale pink, causes the plasma column to contract in size and tends to shift the position of the plasma so that it leans toward the wall of the quartz tube.

The plasma can be stabilized so that it becomes axial by rapidly increasing the pressure (i.e. the mass flow rate) to 250 kPa absolute. When this is done, the N₂ plasma extends from the base of the bluff body along the cavity axis towards the orifice in the bottom plate. The overall appearance of the N₂ plasma column is that it is pinkish in color, has formed in the upper TM₀₁₁ axial maxima and extends along the cavity axis toward the lower maxima and orifice. In comparison to a helium plasma at similar operating conditions, the nitrogen plasma is more compact in diameter but has a greater axial length.

The observed contraction of the helium plasma which resulted from the introduction of the nitrogen is most likely a direct consequence of the difference in thermal conductivities of the two gases. The thermal conductivity of helium at 1000 K is approximately 0.31 W/ (m·°C) whereas the thermal conductivity of nitrogen is 0.0648 W/ (m·°C).¹² There is almost an order of magnitude difference between the thermal conductivities of the two gases. The reduced value of the thermal conductivity of nitrogen results in a decrease in the effective volumetric area which the thermal energy of the plasma core can influence causing a decrease in the radial dimension of the plasma.

Nitrogen Results

The measured parameters of interest are the forward power, the coupling efficiency, mass flow rate, and operating pressure. Once these values are measured values for the potential Iₛ, thrust and system efficiency can be calculated using Equations (19) through (22). The collected data for the TM₀₁₁ tests run with nitrogen are presented in both graphical (Figure 4) and tabular (Table 1) form. All of the presented data is the average of at least three experimental runs.

As can be seen from the data, the range of operating pressure for these tests is limited. The lower constraint is the requirement of choked flow; to insure this condition the pressure must be at least 192 kPa absolute. The upper pressure limit is dictated by the mechanical limits of the quartz tube; the combination of the internal pressure and the thermal stresses introduced by the presence of the plasma limit the operating pressure to 300 kPa absolute; operation above this limit has previously resulted in failure of the quartz pressure vessel. Figure 4 shows the variation in potential Iₛ as a function of specific power; specific power is defined as:

\[ P_s = \frac{P}{\dot{m}} \]  

(23)

where \( P \) is the forward power and \( \dot{m} \) is the mass flow rate.

During the 500 W runs, the plasma was observed to be very stable over the entire pressure range. The term stable refers to a plasma which extends from the base of the bluff body along the cavity axis toward the orifice and does not exhibit a tendency to move toward the walls of the cavity. This type of stability allows the cavity to be tuned such that the coupling efficiency is in excess of 95%. If the plasma is highly stable, the entire plasma column will remain axial at all times, and the free end of the plasma which is directed toward the orifice will not flicker about this ideal axial position. This situation results in a very efficient transfer of thermal energy from the plasma to the flowing propellant gas.

The plot of potential Iₛ vs. specific power for the 500 w case indicate that the increase in Iₛ is an almost linear function of the specific power. The stability of these plasmas allowed for a very efficient transfer of thermal energy to the propellant gas resulting in overall system efficiencies of 31% plus.

The 750 W experimental runs also had stable axial plasmas which resulted in coupling efficiencies of 97%. As the operating pressure was reduced, the specific power increased resulting in a corresponding increase in Iₛ. At low specific powers the plasma was very stable and the trend of a linear increase in Iₛ is observed. As the specific power was increased past 2.75 MW/kg the plasma began to experience a flickering instability. The effect of this is to reduce the amount of heat energy which
was transferred to the propellant gas. This can be seen on
the graph by noting that the upper portion of the curve is
shifted to the right. This indicates that because of this in-
stability more energy per unit mass of propellant is re-
quired to effect the same increase in

The effects of borderline stability were ob-
served in the 1000 W case. At this power level the plasma
had a definite tendency to move toward the coupling
probe; this behavior is detailed in Figure 5. To keep the
plasma from contacting the quartz walls, it is necessary
to purposely detune the cavity thus reducing the coupling
efficiency to approximately 75% - 85%. This unstable
behavior was observed at all power levels, however, the
effect became less pronounced as the operating pressure
was increased. Figure 4 clearly shows the detrimental ef-
fect these large scale instabilities has on the performance
of the resonant cavity thruster.

Figure 6 shows the results of moving the base of
the bluff body closer to the orifice. The data here is for
experiments run at 750 W. Position 1 locates the base of
the bluff body at the transition point in the quartz pres-
sured vessel where the straight tube expands into the
half-hemisphere. Position 2 moves the base of the bluff
body approximately 0.75 cm closer to the orifice. As can
be seen, Position 2 results in an overall increase in per-
formance. Moving the bluff body further into the cavity
decreases the flickering instability of the plasma and in
turn increases the heat transfer to the propellant gas.
Even though this action increases the thermal loss to the
bluff body, the gain in plasma stability offsets this loss.

Because of the operating pressure limitations of
the test rig it proved impossible to maintain a stable ni-
trogen plasma at power levels which were above 1000 W.
The experimental evidence, however, indicates that in-
creased power levels can be reached by increasing the
operating pressure. It also appears that increased pres-
sure can reduce the flickering instability of otherwise sta-
ble plasmas an thus increase the overall system
efficiency.

Ammonia Plasmas

Attempts at forming and maintaining a stable
ammonia plasma at above atmospheric pressures was not
possible using the current test setup. All NH₃ attempts
dealt with the first method described which utilized a
transition from a helium plasma.

The transitions at atmospheric showed that
plasmas which contained a percentage of NH₃ could be
maintained. However, as the fraction of ammonia in-
creased past a certain threshold point the plasma would
extinguish. This threshold increased as the forward pow-
er was increased, but due to excessive heat loads on the
quartz tube, it was not possible to increase the power to
the level required to create a stable atmospheric amm-
onia plasma.

The introduction of a small flow rate of ammo-
nia resulted in a sharp contraction of the plasma columns
as well as an increase in column length; a behavior very
much like that which was observed with N₂. The plasma
also changes color from the purple-white characteristic
color of the helium plasma to a very bright pink. The
contraction of the plasma column can be attributed to the
decrease in thermal conductivity; 0.047 W/ (m°C) for
ammonia gas.²

At atmospheric pressure and 1500 W of input
power the plasma is almost completely NH₃ and the plas-
ma begins to exhibit a pale green color. It is at this point
that the quartz begins to glow because of excessive heat
loading.

Hydrogen Plasmas

Attempts at creating a hydrogen plasma by tran-
sition from a helium plasma were not successful. It was
for this reason that the tungsten wire ignition method was
introduced.

The first tests of this method used a gas mixture
which was approximately composed of equal amounts of
hydrogen and helium at a flow rate which resulted in an
operating pressure of 150 kPa absolute. The tungsten
wire began to glow at an input power of approximately
2.0 kW, and this was accompanied by the formation of a
plasma. Once the plasma was created the cavity could be
tuned such that the coupling efficiency was greater than
90%. As this was accomplished the plasma appeared to
change color from pink to a diffuse orange; this orange
color is attributed to the glowing of the boron-nitride
bluff body which was subject to intense thermal loading.
Attempts to increase the mass flow rate, and thus the
pressure, so as to relieve the heat load resulted in the ex-
tinguishment of the plasma. The operating pressure at
this point was 200 kPa absolute.

While the heavy heat load is definitely a func-
tion of the high input power, the thermal conductivity of
hydrogen should also be considered. Hydrogen’s thermal
conductivity, 0.38 W/ (m°C), is 40% greater than that of
helium and will thus act to increase the amount and
rate at which thermal energy is conducted into the bluff
body.

Additional attempts using this method of igni-
tion all showed promise, but could not be pursued due to
the thermal loads which were induced on the both the
bluff body and the quartz tube.
Advanced Microwave Power Generation

The conventional microwave power source is ill-suited for space applications. The majority of high power microwave generators are used in industrial applications and have not been optimized with respect to overall mass or size. This section describes some of the more advanced techniques which are necessary if high power microwave sources are to be used for onboard spacecraft systems.

The microwave power in most conventional high power applications is generated using a magnetron. The magnetron is a high voltage device which operates at a voltage level of 3000 $V_{dc}$ to 4000 $V_{dc}$. A transformer of some type is required to produce these voltage levels, and it is this component which accounts for most of the device mass. For current space applications, the power supply to the magnetron must take the bus voltage which is typically 150 $V_{dc}$ and transform it to the high voltages required.

The typical industrial power supply uses an iron core transformer to accomplish the transformation to high voltage. A more advanced technique for achieving this high voltage transformation is to utilize a high frequency switching power supply. The principle of such a supply is to take the low DC voltage supply and rapidly switch it at tens of kHz. This procedure produces a high frequency AC signal which can then be transformed to the required high voltage using a conventional transformer. Since the AC signal is at such a high frequency, the power transformer can be much smaller and lighter than the conventional linear 60 Hz power supplies. In addition to the reduced mass, the switching circuit easily allows for the inclusion of power control and regulation systems that provide for better stability. The fact that the transformed and rectified high voltage is at a very high frequency makes it much easier to achieve ripple reduction so that the output waveform has even less ripple than the best of the linear power supplies.\(^\text{13}\)

Power supplies using high frequency switching are commercially available and can operate for hundreds of hours at an overall efficiency of 70%. A rough estimate for the overall system mass for an optimized 5 kW design to be used for space applications is 20.4 kg corresponding to a specific mass of 4.08 kg/kW.\(^\text{14}\)

It may be noted that this specific mass is somewhat higher than the specific masses which are quoted for the high power arcjet power supplies. The difference in the specific masses can be directly related to the high voltage power requirements of each device. The mass of the power processing unit is a very strong function of the required high voltage power, and as the need for high voltage power increases so does the specific mass. A arcjet power supply basically consist of a pulsed low power, high voltage start supply in parallel with a high power, low voltage run supply.\(^\text{15}\) This requirement is in direct contrast with the requirements of a magnetron based microwave generator which requires a high power, high voltage power supply.

Conclusions and Recommendations

The results of these initial test with the molecular propellants N\(_2\), NH\(_3\), and H\(_2\) have indicated that it should be possible to use these gases as propellants in a microwave resonant cavity thruster. While these test were only successful in obtaining quantitative data for N\(_2\), they also indicated that it should be possible to create stable NH\(_3\) and H\(_2\) plasmas using a modified design which would be able to withstand the heavy heat loads produced by these plasmas. The modified design should concentrate on a sturdier design which would use the resonant cavity as the pressure vessel so as to eliminate the need for the quartz tube.

Other design considerations which should be considered are alternate tuning options such as tuning stubs, the axial introduction of the coaxial probe so as to reduce off axis field distortion, and cavity dimension changes which show evidence of enhancing the on axis electric field maximums.

The N\(_2\) results demonstrate the advantages of proper stabilization of the plasma to prevent plasma drift and instabilities. Continued studies, however, are required to more fully qualify this effect.

Acknowledgments

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References


Figure 1a. The electric field configuration of the TM$_{011}$ resonant cavity mode. The cavity length is 7.21 cm corresponding to an operating frequency of 2.45 GHz and a cavity radius of 8.89 cm. There are two axially located maximums, one at L=0.0 cm and the other at L=7.21 cm.

Figure 1b. The electric field configuration of the TM$_{012}$ resonant cavity mode. The cavity length is 10.36 cm corresponding to an operating frequency of 2.45 GHz and a cavity radius of 8.89 cm. There are three axially located maximums, one at L=0.0 cm, the second at L=5.18 cm, and the third at L=10.36 cm.
Figure 2. Resonant cavity geometry used for the TM$_{011}$ experiments. Both the cavity length and the coupling probe depth can be varied independent of each other. The bluff body can be traversed axially.
Figure 3. Schematic of the Experimental Apparatus

A - To Helium supply
B - To secondary gas supply
C - Omega FL-223 Rotameter
D - Mass flow rate control valve
E - Fume hood to exhaust fan
F - Resonant Cavity and quartz tube
G - Flexible waveguide
H - Coax Transition
I - Cavity Pressure
J - Waveguide to Coax Transition
K - Forward power meter
L - Reflected power meter
M - 3-Port Circulator
N - Dummy Load
O - 2.45 GHz Microwave Generator
P - 2.45 GHz Microwave Generator
Q - Vacuum Pump
Figure 4: The variation of specific impulse as a function of specific power for nitrogen propellant
Figure 5. Representation of the characteristics of typically stable and unstable plasmas. For $\text{N}_2$ plasmas at 1000 W of forward power the plasma would become completely unstable and tail off toward the coupling probe causing it to contact the wall of the quartz tube.
Figure 6: The effect of bluff body position on performance. Position 2 corresponds to the base of the bluff body being 0.75 cm closer to the orifice.
Table 1 • Nitrogen Data For Resonant Cavity Operation
In The TM\textsubscript{011} Resonant Mode

<table>
<thead>
<tr>
<th></th>
<th>Coupling Efficiency</th>
<th>Mass Flow Rate (g/s)</th>
<th>Specific Power (MJ/kg)</th>
<th>Potential Isp</th>
<th>Potential Thrust (N)</th>
<th>System Efficiency</th>
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<td><strong>500 W Forward Power</strong></td>
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<tr>
<td>301 kPa</td>
<td>96.39</td>
<td>0.372</td>
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<td>31.38%</td>
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<td>130.34</td>
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<td>13.09%</td>
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