**THE MICROWAVE ELECTRO-THERMAL (MET) THRUSTER:
A NEW TECHNOLOGY FOR SATELLITE PROPULSION
AND ATTITUDE CONTROL**

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Abstract

This paper discusses the current research status of the MET (Microwave Electro-Thermal) thruster. In the MET thruster, an electrodeless, vortex stabilized, plasma is produced in a microwave resonator cavity for the purpose of heating gaseous fuel to produce a high temperature rocket exhaust for space propulsion. The higher specific impulse (momentum transfer per unit weight) of these heated gases offers advantages over traditional chemical rockets in terms of reduced fuel mass. In MET devices, dense plasmas have been produced in various possible fuel gases, nitrogen, hydrogen, and ammonia, using 600 to 2200 Watts of microwave power at a frequency of 2.45 GHz. Ammonia has been found to give a specific impulse of 550 sec. It has been found that the plasma is a 98% absorber of microwave

power leading to negligible reflection of power back to the microwave source and making the cavity operate at low Q. Taking advantage of this effect, it has been found that a very compact MET thruster design could be operated, with the magnetron microwave source and resonator cavity joined in one unit.

Nomenclature

d	length of microwave resonant cavity
e	charge of an electron
E_0	Strength of E field driving a cavity
f_c	frequency of electron neutral collisions
f_p	frequency of electron plasma oscillations
m_e	mass of the electron
n_e	electron number density
N_0	neutral particle number density

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Q Quality factor of microwave resonant
 R radius of microwave resonant cavity
 V_e electron thermal speed
 σ_c electrical conductivity
 σ_0 collision cross section for electrons on neutrals
 $\Delta\omega$ full width at half maximum for microwave resonant cavity
 ω_0 resonant frequency of TM_{011} mode in microwave resonant cavity

I. Background

The MET thruster^(1, 2, 3) is a new electric propulsion technology for space applications and research to develop it is progressing cooperatively at Research Support Instruments, Penn State University and the Center for Space Power at Texas A&M. Research on the MET thruster has also been pursued at NASA Lewis Research Center⁽³⁾.

The presently evolved design for the MET thruster (See Figure) consists of a cylindrical microwave resonator cavity tuned to support the TM_{011} mode, in which a gas vortex is created by tangential injection of gas at high pressure. The use of vortex flows to stabilize free floating microwave discharges was first reported by Kapitsa⁽⁴⁾ and was applied to MET first by one of the authors, M. Micci. The gas forms a high temperature microwave discharge on the axis of the cavity, at the location of one of the antinodes of the electric field in the TM_{011} mode, next to an exit nozzle located on the cavity axis. In the MET it is desirable to heat the gas just as it exits the chamber to minimize heat loss to solid structures, thus the cavity is designed so that the plasma is created at the exit nozzle.

The MET demonstrated at RSI operates at 2.45 GHz and 600W in the TM_{011} mode, because this operating point is

MET Thruster Diagram

Figure: Diagram of New MET Design
(Patent Applied For)

appropriate for the thruster application on small satellites. However, other frequencies, higher powers, and other modes have also been investigated. Investigators at NASA Lewis Research Center⁽³⁾ employed 0.915 GHz microwaves to make MET plasmas using both the TM₀₁₁ and TM₀₁₂ modes. When operating in the TM₀₁₂ mode, the plasma forms in the center of a cylindrical cavity, away from end or side walls. Using the TM₀₁₂ mode the workers at NASA Lewis were able to sustain plasmas at up to 11 kW. Operation at higher power was prevented only by the overheating of a confining discharge tube. The 0.915 GHz frequency was chosen because magnetrons operating at 0.915 GHz are remarkably efficient, with 90% conversion efficiency, making this frequency attractive for high power space applications. Thus, while the research at RSI is presently aimed at perfecting small, low power MET devices, it also appears possible to design large, high power MET thrusters.

The plasma in the MET is very resistive and as a result absorbs approximately 95% of the incident power, which makes the effective Q of the resonant cavity very low. The resistive character of the MET plasma results from the high gas pressure, 1 atmosphere or above, in which the discharge occurs. In recent research it was discovered that because the cavity has low Q, the microwave fields in the cavity can be driven directly by a magnetron generator which has its antenna inserted directly into the cavity. This configuration operates without any apparent loss of efficiency or overheating in the magnetron, and results in an extremely compact thruster design for space applications.

In the remainder of this paper we will discuss the inferred plasma conditions in the MET cavity and how they allow a compact MET design to be realized.

II. The Physics of the MET Cavity

The MET thruster operates as a heavily damped resonant cavity. The existence of a low order mode in microwave resonant cavities fixes the electric field geometry inside to create a region of strong electric field in the cavity whose location can be controlled. This, in turn, allows the location of the breakdown and the sustained discharge to be controlled. The existence and properties of the plasma in the MET cavity heavily load the cavity, damping the resonant fields and making the conditions of resonance insensitive to the details of the cavity geometry.

Vortex gas flow reinforces the tendency of the plasma to remain in a region of intense electric field in the resonant field and prevents the problem of plasma migration to the microwave antenna, a phenomenon observed in previous experiments without vorticity⁽³⁾. The presence of vortex flow thus stabilizes the resonant fields by stabilizing the plasma location. Vortex stabilized, low order mode cavities have been run successfully at both 2.45 GHz and 0.915 GHz, in both TM₀₁₁ and TM₀₁₂ modes. The TM₀₁₂ mode is similar to the TM₀₁₁ mode and can be excited in resonators that are only slightly different from those that support TM₀₁₁. The conditions for resonance in a cylindrical cavity⁽⁵⁾ for 2.45 GHz microwaves are:

$$\begin{aligned} \text{TM}_{011} : & \quad c \cdot (x_{01}^2/R^2 + \pi^2/d^2)^{1/2} \\ & = 2.45 \cdot 10^9 \text{ sec}^{-1} \end{aligned} \quad (1a)$$

$$\begin{aligned} \text{TM}_{012} : & \quad c \cdot (x_{01}^2/R^2 + 4\pi^2/d^2)^{1/2} \\ & = 2.45 \cdot 10^9 \text{ sec}^{-1} \end{aligned} \quad (1b)$$

where c is the speed of light, R is the cylinder radius, d is its length, and $x_{01} = 5.520$ is the first zero of Bessel function $J_0(x)$. For the same value of R in the TM₀₁₂ mode, the length d must be twice that used for TM₀₁₁. In both modes E

field lines concentrate at locations along the axis of the cavity creating regions where plasma will form preferentially.

The process of plasma formation in gases by microwaves has been studied extensively, both experimentally and theoretically⁽⁶⁾. Because of the high collisional frequency of electrons with neutrals and ions in a discharge at one atmosphere, there is little change in the physics of the discharge between operation at 2.45 GHz or 0.915 GHz. This follows from the fact that the electrons in the plasma experience E field acceleration for much less than one cycle of the external wave field oscillation before they collide with neutrals or ions and scatter. The collision frequency of electrons with neutrals and ions in a 1 atmosphere pressure discharge with electron temperatures of 11,000 K (1 eV) is approximately found as

$$f_c = \sigma_0 \cdot N_0 \cdot V_e \approx 10^{11} \text{ sec}^{-1} \quad (2)$$

where $\sigma_0 \sim 1.5 \cdot 10^{-16} \text{ cm}^2$ is the cross section for collisions of 1 eV electrons with neutral atoms, $N_0 \sim 10^{19} \text{ cm}^{-3}$ is the approximate neutral particle density in the discharge at 1 atmosphere, and $V_e \sim 6 \cdot 10^7 \text{ cm/s}$ is the thermal velocity of 1 eV electrons. At $f_c = 10^{11}$, the collision frequency is thus much higher than the microwave frequency even at 2.45 GHz. Therefore the plasma electrons experience the wave fields as a series of dc accelerations, rather than an oscillating field.

MET plasmas are inherently absorptive, due to a high rate of electron collisions with neutrals and ions.

The plasmas produced in the MET exhibit visible light extinction lengths of a few millimeters, indicating approximate electron densities of approximately $n_e = 10^{14} \text{ e}^-/\text{cm}^3$. The

plasma frequency in this case is approximately

$$f_p = (4\pi e^2 n_e / m_e)^{1/2} / 2\pi \approx 9000 \cdot n_e^{1/2} \quad (3)$$

where e is the electron charge and m_e is the electron mass, so that f_p is approximately 10^{11} Hz . This is approximately the same as the collision frequency, therefore, the electrons in the plasma are therefore dominated by collisional rather than collective effects, and as a consequence resemble high pressure arc discharges⁽⁷⁾. The flow of electrons in such a discharge resembles that in an ordinary conductor like carbon, rather than in a collisionless plasma.

Since the electron motion is heavily impeded by collisions, such a discharge is inherently lossy and tends to be an absorber of electromagnetic energy rather than a reflector. At 11,000 K, the conductivity of a plasma in 1 atmosphere gas is found approximately as

$$\sigma_c = (e^2 n_e / m_e) / f_c = f_p^2 / (4\pi f_c) \approx 10^{10} \text{ s}^{-1} \text{ in esu units} \quad (4)$$

or

$$1 \text{ mho/m in MKS units,}$$

which is somewhat lower than the conductivity of carbon at room temperature. Since the plasmas in the MET occupy approximately 10% of the volume of the cavity, and furthermore occupy that region where most of the electric field energy is stored in the cavity, the resistive plasma exerts a strong damping on the cavity, making it a low Q cavity.

The fact that the value of the plasma conductivity leads to low Q can be seen easily by the expression⁽⁸⁾ for Q

$$Q = \omega_0 (\text{Stored energy}) / (\text{Power Loss})$$

$$\approx \omega_0 E^2 / (8\pi\sigma_c E^2) \approx \omega_0 / 8\pi\sigma_c \approx 1 \quad (5)$$

where we have used the approximation that the plasma occupies the region where E fields are strongest and thus where most of the E field energy is stored.

The Q of the MET cavity is thus of order unity whereas a normal metal cavity has Q of the order of 1000 or greater. This has the consequence that the resonance line width of the cavity, the range of frequencies around the fundamental frequency at which the cavity will resonate, is broad being of the order of the frequency.

$$\Delta\omega = \omega_0 / Q \quad (6)$$

This also means that the E field strength in the cavity is approximately the same as the E field driving the cavity which is, the E field near the antenna radiating microwaves into the cavity, since the E fields in the cavity are related to the driving E fields E_0 by the relation

$$E = QE_0. \quad (7)$$

Therefore the antenna of the microwaves will see low E fields in the cavity when it radiates and thus microwave power will tend to flow into the cavity and not out of it. The low Q of the MET cavity thus allows the direct application of microwaves from the generator without concern that reflected power will harm the generator. This hypothesis was then verified by experiment, where a magnetron was inserted directly into the cavity and drove the discharge with no measurable change in plasma or magnetron operation.

III. Summary

Therefore the operation of the MET thruster cavity is crucially dependent on the presence of the plasma that heats the fuel gas. This plasma transforms the cavity from a high Q cavity to a low Q

cavity with the attendant effects of low E fields in the cavity, resonance broadening and negligible reflected power. These effects made the direct joining of the cavity to the magnetron possible and successful. The result is a compact design for which a patent has been applied for.

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