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OPTIMIZATION OF ENERGY TRANSFER IN MICROWAVE ELECTROTHERMAL THRUSTERS

D. J. Sullivan and M. M. Micci

Propulsion Engineering Research Center
Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA 16802

SUMMARY

Results are presented from preliminary tests conducted to evaluate the performance of a prototype microwave electrothermal thruster. The primary component of the device is a microwave resonant cavity. The device produces stable axial plasmas within a pressurized section of the cavity with the plasma positioned in the inlet region of the nozzle. Plasma stability is enhanced by axial power coupling, an optimal distribution of electric power density within the cavity, and a propellant gas flow which has a large vortical velocity component. The thruster has been operated with a number of propellant gases: helium, nitrogen, ammonia, and hydrogen. Plasmas can be formed in a reliable manner at cavity pressures of 1 kPa and incident power levels ranging from 50 W to 350 W, depending on the gas used, and can be operated at pressures up to 300 kPa at power levels up to 2200 W. Ideal performance results of vacuum Isp and thermal efficiency vs. specific power are presented for each gas.Representative results of this preliminary work are: He - Isp = 625 s, $\eta_{thermal}$ = 90%; N_2 - Isp = 270 s, $\eta_{thermal}$ = 41%; NH_3 - Isp = 475 s, $\eta_{thermal}$ = 55%; H_2 - Isp = 1040 s, $\eta_{thermal}$ = 53%.

TECHNICAL DISCUSSION

For the past decade, the development of a microwave powered electrothermal thruster has been pursued by a number of researchers using both experimental and numerical methods [Ref 1-5]. The experimental work conducted at Penn State [Ref. 2-5] has explored the viability of thruster configurations which have incorporated either rectangular or cylindrical waveguides, or cylindrical resonant cavities as their central components. 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 powered thruster 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 results of previous experimentation at both Penn State and some recent work which has been initiated at NASA LeRC [Ref. 5], and examination of considerable computational [Ref. 4] and analytical studies [Ref 3] have been used to develop a design for a first-generation microwave resonant cavity thruster prototype which has been designed to produce optimal performance while correcting many of the undesirable operational features of the earlier Penn State devices, in particular, movement of the plasma discharge to off-axis positions at high power operation.; a schematic of the device is shown in Figure 1. The main component of the prototype thruster is a resonant cavity which operates in the TM_{011} mode, this mode is optimal for producing an axial, free-floating plasma. The thruster is designed such that the plasma forms directly upstream of a nozzle inlet which has been fabricated into the stationary short of the cavity. The formation of the plasma discharge near the inlet of the nozzle produces the most efficient transfer of thermal energy to the propellant gas.

The cavity geometry has been chosen such that it concentrates the electric field density pattern within the cavity at the upstream and downstream axial regions, while at the same time producing a relatively low field density in the characteristic annular region located at the midpoint of the cavity. The cavity diameter of 10.16 cm (4.0 in) was chosen to produce this desired electric field density distribution as well as to facilitate fabrication. The cavity is constructed of brass and its interior has been highly polished to remove metal oxides so as to increase the electrical conductivity. At the operating frequency of 2.45 GHZ, the ideal resonant length for a cavity of this diameter is 15.87 cm.

The off-axis motion of the plasma which was a significant problem for the original Penn State cavity has been attributed to a poor electric field density distribution and an asymmetrically positioned coupling probe which was introduced into the side of the cavity. This asymmetric introduction of the coupling probe produced a nonaxisymmetric distortion of the electric field density pattern which tended to "push" the plasma away from its position on the central axis. 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 smaller radius cavity of the prototype produces a longer resonant length and results in a more favorable electric field density distribution. 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 geometry of the prototype design is flexible and the microwave circuit incorporates a three-stub tuning device. A combination the proper cavity geometry and the settings of the tuner allow the system to be fine tuned producing optimal performance at a specified operating condition Once theses settings are determined, it should be possible to fix that given geometry in a future design and remove the requirements for any moving parts.

The prototype has removed the need for any quartz vessels by making one entire half of the cavity the pressure chamber. This has been accomplished by incorporating a pressure plate at the midplane of the cavity. The plate is 0.32 cm (1/8 in) thick, and it is constructed from a low loss microwave dielectric. The prototype incorporates three gas injection ports which produce a swirling flow that 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; the swirling flow pattern enhances the axial stability of the plasma. Optical access of the plasma is made possible by a view port located in the wall of the pressure section of the cavity.

The prototype thruster has been successfully operated using helium, nitrogen, hydrogen, and ammonia propellants. The device is able to form plasmas from all of these propellant gases in a reliable and repeatable manner. The formation process occurs at pressures which are below atmospheric, typically less than 1 kPa, and at power levels ranging from 50 W to 750 W depending upon the propellant gas. For each gas, the plasma discharge can be maintained while the pressure within the cavity is increased to pressures which are above atmospheric; typically between 100 kPa and 350 kPa. The upper limit depends upon the propellant gas, the amount of available power, and the efficiency of the power coupling. Excellent power coupling can be achieved with typically greater than 98% of the incident microwave power being coupled into the plasma discharge at incident power levels of 1000 W.

The initial tests conducted with the prototype utilized helium as the propellant gas. Helium is a monatomic gas and thus is easy to breakdown; typically at 1 kPa the power required for breakdown was less than 50 W. The plasma discharge was very well behaved and it proved very easy to increase both the power and pressure; at the high range of the operational envelope examined, the plasma could be maintained at 2200 W and 340 kPa. The use of helium allowed the performance of the prototype to be compared to that of the original Penn State cavity which was also extensively tested with helium propellant. The performance results (Figure 2a and 2b) are presented in terms of vacuum specific impulse and thermal efficiency vs. specific power. The specific impulse estimates are calculated assuming an ideal isentropic expansion to vacuum. The better performance of the prototype can be primarily attributed to the fact that the plasma discharge is located directly within the nozzle inlet. The plasma produces a significant flow blockage which results in relatively high pressures for moderate flow rates, and the gas which exits the nozzle is heated to very high temperatures as it passes through the constricted region between the plasma discharge and the nozzle wall. Ideal I_{sp}'s as high as 657 s with thermal efficiencies of 70 % were obtained.

The next series of tests used nitrogen as the propellant. This testing verified that the prototype could produce and maintain plasmas formed from molecular propellants over a large operating range of pressures and powers. The nitrogen plasmas typically formed at pressures of 1 kPa through the application of approximately 100 W of incident power. The plasma discharge was stable and well behaved; a typical operating condition was 350 kPa and 1875 W incident power with 93% power coupling (the three-stub tuner was not used during these tests) resulting in an ideal I_{sp} of 268 s at a specific power of 7.5 MJ/kg with a thermal efficiency of 41%.

The prototype thruster was also operated using ammonia as a working fluid. Ammonia plasmas can be repeatedly and reliable formed at pressures of 1 kPa with the application of approximately 750 W. The higher power required to initiate the breakdown process is a reflection of the greater degrees of freedom of the ammonia molecule. As with the other gases, the plasma is stable and well behaved; a typical operating condition was 147 kPa and 1514 W incident power with 99% power coupling resulting in an I_{sp} of 422 s assuming an ideal equilibrium expansion to vacuum (frozen expansion Isp is 372 s) at a specific power of 21 MJ/kg with a thermal efficiency of 63%.

Hydrogen plasmas have also proven to be easy to produce, typically at 1 kPa and 300 W, are well behaved, and it is possible to operate the plasma at pressures up to 100 kPa. The performance results (Figure 3) do not represent optimal testing conditions. The data shown was taken to verify operation with hydrogen and to explore the pressure range through which the plasma can be maintained; better performance can be achieved by operating the thruster at higher chamber pressures. The performance data takes dissociation into account through the use of a chemical equilibrium code. A typical operating condition was 100 kPa and 1803 W incident power with 97% power coupling resulting in an I_{sp} of 1020 s assuming an ideal equilibrium expansion to vacuum (frozen expansion Isp is 907 s) at a specific power of 95 MJ/kg with a thermal efficiency of 50%.

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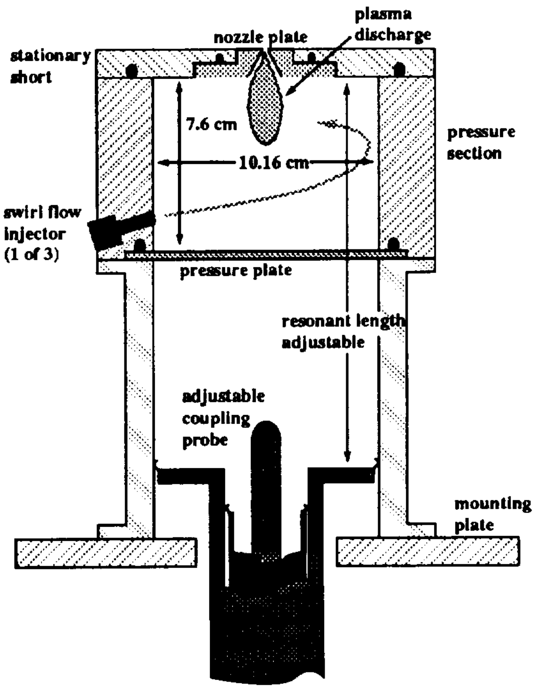

Figure 1: Schematic of the microwave resonant cavity electrothermal thruster prototype. The diameter of the cavity is 10.16 cm and the theoretical resonant length is 15.87 cm. The plasma discharge forms on the axis of the cavity within the inlet of the nozzle.

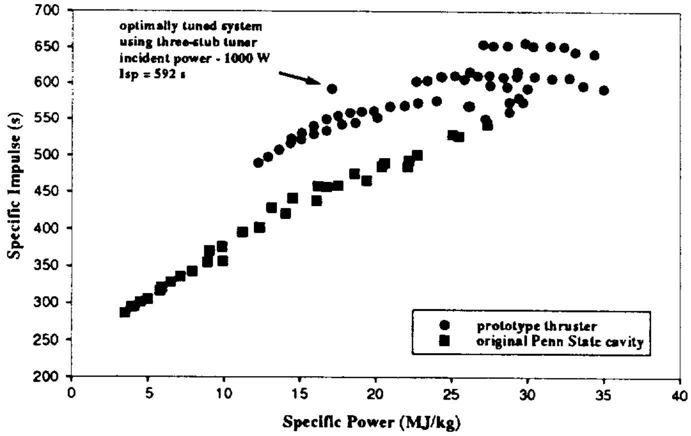

Figure 2a: • Helium Propellant • Performance data comparing the prototype microwave electrothermal thruster with that of the original cavity used at Penn State. The performance of the system when the three-stub tuner is used is noted for an optimally tuned condition at 1000 W.

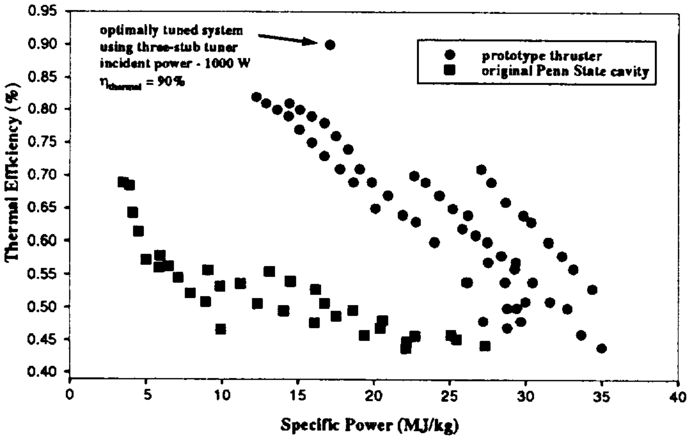

Figure 2b: • Helium Propellant • Thermal efficiency data comparing the performance of the prototype microwave electrothermal thruster with that of the original cavity used at Penn State. The drop off in efficiency results from poor tuning at higher power levels; this can be corrected by including the three-stub tuner into the system.

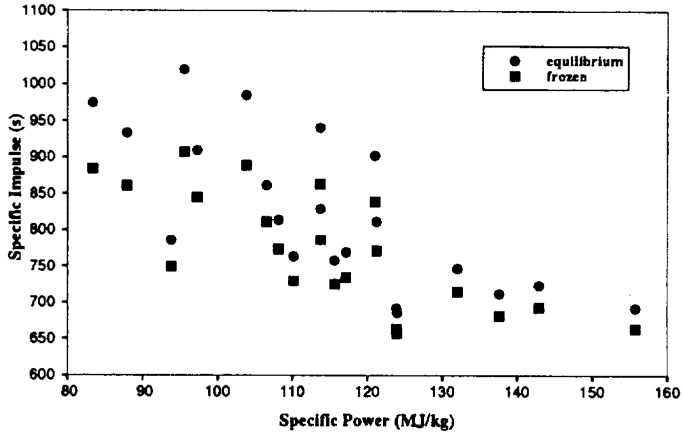

Figure 3: • Hydrogen Propellant • Preliminary performance data. Results account for the dissociation of the H_2 molecule. Isp is presented assuming both equilibrium and frozen flow expansion to vacuum.