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Investigation of Stabilized Resonant Cavity Microwave Plasmas for Propulsion

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Results are presented for the performance of a microwave electrothermal thruster utilizing bluff-body and swirling flow stabilized plasmas with helium and nitrogen propellant. Stabilized plasmas have been produced in the TM_{011} electromagnetic cavity mode with coupling efficiencies approaching 100% and specific powers up to 27.3 MJ/kg. Fluid dynamic measurements indicate specific impulses of up to 543 s, efficiencies of 44–69%, and thrusts of 0.27–0.40 N with helium propellant. Spectroscopic results indicate plasma core electron temperatures of 11,840–12,170 K with extremely flat radial profiles.

Nomenclature

A = orifice area, m
c = speed of light, m/s
c_p = specific heat, J/kg K
g = gravitational acceleration, m/s^2
I_{sp} = specific impulse, s
k = Boltzmann's constant, J/K
m = particle mass, kg
$\dot{m}$ = mass flow rate, kg/s
P_i = incident power, W
Po = chamber pressure, Pa
P_r = reflected power, W
R = gas constant, J/kg K
T_f = thrust, N
T_{0c} = stagnation temperature (cold), K
T_{0h} = stagnation temperature (hot), K
u_e = exhaust velocity, m/s
γ = ratio of specific heats
η = efficiency
η_c = coupling efficiency
λ = wavelength, Å

Introduction

THE current emergence of electric propulsion, and particularly electrothermal systems, as viable and attractive alternatives to chemical propulsion systems aboard both communications and scientific spacecraft has increased the interest in understanding the basic processes that take place in such systems, with the goal of improving the I_{sp}, thrust, and system efficiency. Much effort has been focused upon development of the arcjet, and it is this electrothermal system that is currently flight qualified. There is, however, considerable performance improvement possible over that of the existing arcjet thrusters by removing the electrodes, which are a source of considerable heat loss. Electrodeless thrusters potentially offer significantly higher efficiencies and I_{sp} for the same input power and mass flow rate.

This research program has focused upon developing a microwave electrothermal thruster whereby an electrodeless plasma is formed within a microwave resonant cavity and subsequently used to heat a propellant gas prior to expansion through a fluid dynamic nozzle. Previous work has demonstrated the ability to generate and sustain high-pressure plasmas with helium and nitrogen gases in the TM_{012} cavity mode at a frequency of 2.45 GH,[1–5] and preliminary experiments indicated that efficiencies substantially higher than those typical of arcjets were possible. It was also found, however, that in order to operate at powers and pressures of interest to real applications, it is necessary to axially stabilize the plasma in the thruster, which is consistent with results found in other studies of electrothermal thrusters. Two methods of plasma stabilization have been investigated in this research, those of bluff-body and swirling flow stabilization, which are the most commonly used in combustion systems. These fluid dynamic techniques have previously been used in electrothermal systems with varying degrees of success. A survey of the work performed in this field has been made elsewhere, which identifies the various methods used and the results obtained.[3,4]

The behavior and performance of the stabilized plasma systems investigated here are presented as a function of stabilization device, input power, chamber pressure, and mass flow rate, and include calculations of electromagnetic coupling efficiency, thruster efficiency, specific impulse, and thrust. Of particular interest is the presentation of the results as a function of specific power, which allows a more or less direct comparison with published results from other electrothermal systems. Also performed were spectroscopic measurements of the plasma electron and heavy particle temperatures, which allow some assessment of the physical processes taking place within the plasma.

Experimental System

The system used for these experiments is very similar to that previously described for the experiments with the TM_{012} mode.[1–5] The microwave and cooling systems are identical, and the same safety considerations are applicable. The major differences are in the design of the plasma containment vessel, the use of stabilizing devices, and in that the TM_{011} mode was employed, with subsequently different cavity lengths from those used in the previous experiments.

The plasma containment vessels used in these experiments were clear quartz cylinder-hemisphere combinations. They were designed to be used in the TM_{011} resonant cavity mode, with a 75-mm-diam hemisphere and a 22-mm-wide flange with eight equispaced bolt holes, which were designed to mate with matching holes in the orifice plate. Two vessels were manufactured, one for each stabilization scheme. The first, used with the bluff body, has a tube with an i.d. of 24.5 mm, a wall thickness of 2 mm, and a flange thickness of 6.5 mm. The second, for use with the flow swirler, has a reduced i.d.

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(20 mm) to provide a close fit with the boron nitride swirler, and reduced wall and flange thicknesses (1.5 and 3.25 mm, respectively). These reduced thicknesses were chosen because it was found unnecessary to have the thicker dimensions of the first vessel.

The gas supply system for these experiments is shown schematically in Fig. 1. A removable orifice plate was used to produce a choked exit flow of propellant. Boron nitride (HBC grade) was selected as the material for the plate, as this is a high-temperature dielectric and is capable of operating near the plasma in the microwave cavity. A 30-deg half-angle converging nozzle was machined into the plate, with an exit diameter of approximately 0.8 mm. This diameter was chosen to allow mass flow rates of the order 0.1 g/s to be used, thus allowing specific powers of up to about 25 MJ/kg to be applied, which corresponds to the typical level investigated in recent research and development of low-power arcjets.

The major material requirements for both the bluff body and the flow swirler are the same as for the orifice plate, they should act as dielectrics in the resonant cavity and be capable of withstanding the high temperatures that are present in the proximity of the plasma. Boron nitride components have previously been used in the stabilization of waveguide-generated plasmas and this material was chosen for the current experiments. The maximum operating temperature of boron nitride is estimated at 3230 K, above which significant dissociation of the B—N bonds takes place. The use of a sealed screw-thread system allows either device to be vertically traversed with respect to the plasma and containment vessel.

The bluff body is shown in Fig. 2, and consists of a 12.5-mm stem and a 30-deg conical end. The base diameter of the bluff body is 19 mm, which yields a blockage ratio of 0.60 when located within the quartz tube upstream of the hemisphere. The flow swirler, shown in Fig. 3, is essentially an extremely coarse thread machined onto a boron nitride rod. The inclination of the helical thread to the swirler axis is approximately 60 deg and the core diameter is approximately 8.5 mm. The thread o.d. was finished by hand to obtain a close fit with the quartz tube upstream of the hemispherical plasma containment region. With these dimensions a swirl number, which is the ratio of the angular to the axial momentum of the fluid, of approximately 1.3 may be calculated,[4] which indicates the presence of a strongly swirling (i.e., recirculating) flow downstream of the swirler.

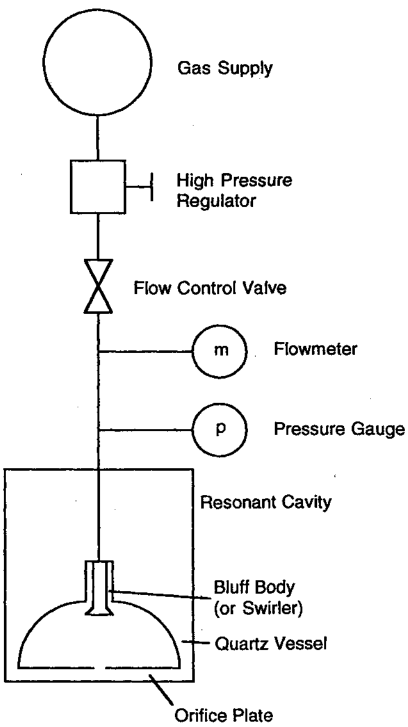

Fig. 1 Schematic of experimental flow system.

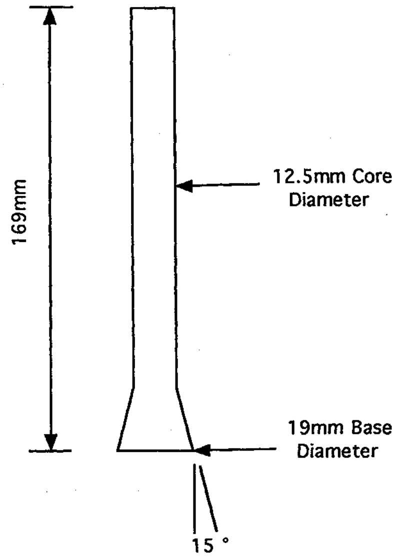

Fig. 2 Boron nitride bluff body.

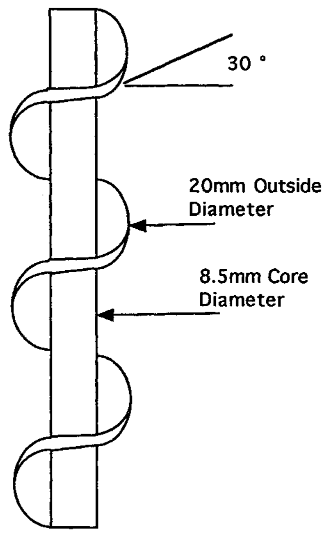

Fig. 3 Boron nitride flow swirler.

The spectroscopic system is based upon a Spex 0.5-m spectrometer and a Fabry–Perot tunable etalon. The results presented here were obtained using fused silica optics and a simplified optical train as described elsewhere.[4] The collimating apertures that were used allowed a spot diameter of 2.1 mm to be observed, thus allowing radial scanning of the plasma, while the Fabry–Perot system allows a maximum spectral resolution of the order 0.004 Å to be obtained at the wavelengths of interest.

Experimental Procedure

Plasma Ignition

A low-pressure ignition technique was used, whereby the chamber pressure was reduced to approximately 6 kPa and approximately 100 W of microwave power applied. This method has previously been demonstrated[1–5] and is an extremely repeatable method of plasma ignition.

Coupling Efficiency

Measurements of the incident and reflected microwave powers were taken at each combination of incident power and pressure in order to determine the power absorbed by the plasma and the resulting electromagnetic coupling efficiency η_c. In contrast to those previously made, however, the calculations of the coupling efficiency neglect the ohmic losses to the cavity walls, which are typically small compared to the incident power. The coupling efficiencies are thus evaluated using the following expression:

$$\eta_c = [(P_i - P_r)/P_i] \times 100\% \quad (1)$$

Specific Impulse, Efficiency, and Thrust

The mass flow rate through a choked nozzle of area A is given by[6]

$$\dot{m} = \frac{AP_0\sqrt{\gamma}}{\sqrt{RT_{0h}}}\left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/2(\gamma-1)} \quad (2)$$

where T_{0h} is the stagnation temperature of the gas upstream of the orifice, which may thus be calculated using measurements of P_0 and $\dot{m}$. It is then possible to obtain an estimate of the potential I_{sp} of the device (assuming an ideal expansion to vacuum):

$$I_{sp} = \sqrt{2c_pT_{0h}}/g \quad (3)$$

The system efficiency may be calculated using measured quantities by

$$\eta = (\dot{m}c_p/P)(T_{0h} - T_{0c}) \quad (4)$$

where T_{0c} is the stagnation temperature of the cold gas upstream of the plasma, P is the incident microwave power, and c_p is the specific heat of the gas at constant pressure. The thrust of the system may similarly be estimated from the mass flow rate (assuming an ideal expansion):

$$T_f = \dot{m}u_e \quad (5)$$

From these equations it is possible to estimate the effect of experimental errors upon the calculated I_{sp}, thrust, and efficiency. The errors in power and mass flow rate measurements are estimated to be approximately ±1 and ±6%, respectively, and a conservative estimate of the error in pressure measurements from commercial gauges is ±3%. These combine to produce overall errors of ±9, ±3, and ±13% in the calculated values of I_{sp}, thrust, and overall efficiency.

The method used for determination of the electron temperature T_e is the commonly used absolute continuum method. In this method, absolute measurements of the continuum emission coefficient are used together with values of the electron number density (obtained in the research presented here by using the Saha equation) to directly calculate T_e. The use and limitations of this technique are well known, and have been previously discussed.[4,7]

Results and Discussion

The results presented in the following sections are for plasmas generated in the TM_{011} mode that have been stabilized by either a bluff body or a swirling flowfield. Most of the results are for helium plasmas, although tests with nitrogen have been conducted and are presented to compare and contrast with the helium behavior. The maximum chamber pressure used in most cases was 300 kPa. Early tests were run at pressures of up to 500 kPa, but subsequent failure of the quartz vessel resulted in limiting the maximum pressure to 300 kPa. The maximum power output from the magnetron is approximately 2.5 kW, although the maximum power used in these experiments was 2.25 kW due to excessive quartz heating by the plasma. Measurements were taken at 250-W intervals up to 2 kW. Where numerical values are presented, they are the average of a minimum of three experimental runs under the same conditions.

Ignition and General Behavior

Low-pressure plasma ignition was obtained in a similar manner to that previously described. Ignition without a stabilization device was instantaneous and extremely repeatable. The plasma formed in the straight section of quartz tube upstream of the hemisphere, in a position corresponding to the upper node of the TM_{011} mode. As was found for all of the tests at low pressure, the plasma appeared as a diffuse "cloud," filling much of the tube cross section and located centrally on the tube axis. As the chamber pressure was increased, the plasma contracted into a more filament-like shape, and moved away from the tube axis to a position such that it was in contact with the quartz tube where the sliding short was located. The position to which the plasma moved was consistently the same side of the cavity as the coupling probe. Similar behavior was observed when the incident power was increased, except that the plasma grew slightly larger in the radial direction and extended further downstream in the axial direction.

Bluff-Body Stabilized Plasmas

With the bluff body present, plasma ignition could be achieved repeatably at low powers and pressures. The plasma appearance was the same as previously observed without a stabilization device, that of a diffuse pink cloud. The majority of time the plasma would form just downstream of the bluff body, corresponding to the position of the upper node of the cavity (i.e., at the upstream end), and was therefore located in the cylindrical region of the quartz container, rather than in the hemispherical region. An optimal bluff-body location was found by trial and error where the plasma was slightly in contact with the base of the body (behavior that has also been observed in numerical models of this system[8]), and was firmly held in place by the recirculation zone. It was possible to vary the incident power and chamber pressure (or equivalently, the mass flow rate) in order to observe the plasma characteristics and behavior under different operating conditions. At a given chamber pressure, increasing the incident power resulted in an increase of both the diameter and length of the plasma. This was a problem at low pressures and high powers, as the plasma expanded to fill most of the quartz tube, resulting in rapid heating of the quartz.

The increase in plasma length with increasing power (at a given chamber pressure) yielded some interesting observations. As the plasma extended downstream into the hemispherical region it changed from an intense filament-type plasma to one that was more diffuse in this "tail" region, as if the plasma had expanded due to physical expansion of the quartz vessel. As the power was increased further, the plasma tail extended towards the converging orifice and at sufficiently high powers was in contact with the orifice in a "funneling"-type effect. It was also observed that there was a strong influence on this diffuse tail arising from the coupling probe. The tail curved slightly towards the coupling probe before resuming an axial location at the orifice. Further increase of the power resulted in the tail region near the orifice becoming more intense, indicating that the increased power was being absorbed by the plasma in the region corresponding to the lower electromagnetic node. At these higher powers it appeared as if the plasma consisted of two regions of strong electromagnetic absorption joined by a more diffuse region. This transition (for helium plasmas) of the tail to and from the orifice region was extremely smooth with no evidence of any discontinuity or jump in physical position or absorbed power. Slightly different behavior was observed for nitrogen, which is discussed later. The effect of increasing chamber pressure was essentially opposite to that of increasing power; the plasma reduced in both diameter and length and it was possible to control the extent of the plasma tail by varying either the power or the pressure.

Most of the tests conducted were of approximately 5–10 min duration, and so it was decided to perform a longer duration test at high powers to see if there were any stability or erosion problems that did not develop in the short tests. To this end, a test with helium was performed at 1.5 kW and 300 kPa for 90 min, followed by 20 min at 2 kW and 400 kPa. No measurable change in behavior or performance was observed in either phase of the test and posttest inspection revealed no damage or erosion to the bluff body, quartz vessel, or orifice plate.

Experiments revealed that there is a significant difference between operation with nitrogen and helium. As was observed in the tests in the TM_{012} mode, nitrogen plasmas were more difficult to ignite than helium plasmas because of the greater number of modes of internal energy storage of the molecular gas. Once ignited, the plasma was held strongly in position in the recirculation zone of the bluff body, although unlike the tests with helium, there was a clear gap of about 6 mm between the nitrogen plasma and the base of the bluff body. This indicates that a molecular plasma can be generated and sustained in the wake of a bluff body without any physical contact with the body itself. The plasma is thus effectively kept away from all solid surfaces, allowing more of the power absorbed by the plasma to be transferred to the flowing gas. It was also possible to maintain nitrogen plasmas at pressures significantly above atmospheric, which was not possible in the TM_{012} mode.

The effects of power and pressure upon nitrogen plasmas were also different from those observed with helium. As the power was increased, the plasma tail extended towards the exhaust orifice, as was the case for helium, but this funneling effect was observed to be far more significant for nitrogen. Increases in incident power above approximately 700 W resulted in a lifting of the plasma tail away from the orifice region. This transition consisted of a sharp jump away from the orifice towards the center of the hemisphere, in contrast to the smooth behavior observed with helium. This lifting away from the orifice region was accompanied by an increase in reflected power from the cavity, which is indicative of a lack of tuning. Further increase in incident power moved the plasma tail further away from the orifice and extended it in the direction of the coupling probe. An increase in chamber pressure above approximately 170 kPa produced similar behavior in that the plasma lifted away from the orifice, although in this case a slight reduction in size accompanied the movement. Once again the transition was not smooth and was accompanied by an increase in reflected power.

Swirling Flow Stabilized Plasmas

The same low-power, low-pressure ignition was also possible with the flow swirler in the chamber. It was found that the plasma formed at the mouth of the hemisphere and that this location was insensitive to changes in swirler position. However, it was found that the plasma was positionally extremely sensitive to changes in either incident power or pressure. Even slight increases in either of these parameters resulted in an excursion of the plasma from its original position at the mouth of the hemisphere, down the sides of the hemispherical quartz vessel to the boron nitride orifice plate. The inability to increase either power or pressure prevented the same level of investigation as for the bluff-body stabilized plasmas. Tests with nitrogen produced identical behavior to those with helium in all swirler positions. This was surprising considering the differences in behavior observed with the bluff body, although these differences were observed at pressures above those that were reached in the swirler tests.

Coupling Efficiency

The coupling efficiencies for bluff-body stabilized helium and nitrogen plasmas are shown in Fig. 4 as a function of pressure for different input powers. For helium plasmas it is possible to tune the cavity (i.e., reduce the reflected power to zero or nearly zero) over a wide range of operating conditions. With the exception of the 250-W input power case, the efficiencies are extremely flat with respect to pressure and are in the range of 95–100% for all cases with a slight decrease as the incident power is increased. The 250- and 500-W power cases correspond to those in which the maximum pressure for which a plasma can be sustained is being reached and further increases result in the observed characteristic rise in reflected power and resulting decrease in coupling efficiency. As previously discussed, this occurs at about 240 kPa for 250-W input power and about 300 kPa for 500 W. The results for 750 W and greater powers show very flat efficiency profiles over the entire pressure range investigated. Single tests at 1000 and 1500 W were conducted at up to 500 kPa, and it was found that no increase in reflected power was observed, even at such elevated pressures.

Due to the positional instability that was observed, only limited results were obtained with nitrogen plasmas. The results obtained, however, indicate that very high coupling efficiencies are possible, approaching 100%, until the tail of the plasma lifts away from the orifice region and moves towards the coupling probe as has been described. This positional instability was accompanied by an increase in reflected power and a corresponding decrease in efficiency.

These results differ from those obtained in the TM_{012} mode, where the maximum coupling efficiency was measured to be about 80%, and where a distinct peak in efficiency was observed when plotted against chamber pressure.[1-5] The difference in magnitude may be explained as a combination of two effects. Firstly, the wall losses have not been taken into account in the present calculations (whereas they were allowed for in the TM_{012} calculations), and secondly, optimal tuning of the cavity was possible with the stabilized plasma without damaging the quartz container. This was not possible with the unstabilized plasma in the TM_{012} mode due to the excursion of the plasma to the quartz surfaces. It is possible that the observed peak in coupling efficiency in the TM_{012} experiments is partly due to the lower powers that were used (up to 450 W), although the current results at 500 W (and to some extent at 250 W) do possess much flatter profiles. This improved behavior may be attributed to the axial positioning of the plasma under the bluff body in the current experiments, compared to the significantly asymmetric position observed in the unstabilized TM_{012} tests.

Similar high coupling efficiencies for both helium and nitrogen plasmas have been reported in previous research over

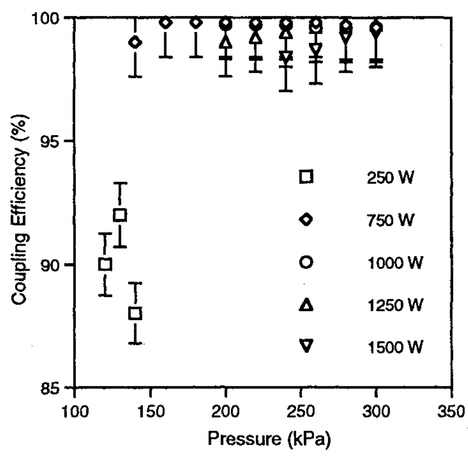

Fig. 4 Coupling efficiencies for bluff-body stabilized helium plasmas.

a wide range of operating conditions[9] and analytical studies have predicted that, in high-pressure microwave plasmas, there should be minimal tuning required for resonance,[10] which was indeed observed. The insensitivity of the coupling efficiency to the operating conditions and the minimal tuning requirements are attributed to the lossy nature of the plasma whereby the resonant cavity quality factor is reduced and the plasma-cavity system effectively adjusts to the conditions present.[10,11]

Overall Efficiency, Specific Impulse, and Thrust

The overall efficiency for bluff-body stabilized helium plasmas is presented in Fig. 5 as a function of specific power for a series of incident powers. It can be seen that η increases with increasing pressure and decreases with increasing power. Increasing the pressure increased the mass flow rate through the system, increasing the heat transfer to the flowing gas. Increasing the pressure also reduced the plasma diameter in a constricting effect. In the region where the plasma is stably located beneath the bluff body, this constricting effect has the effect of reducing the heat load to the quartz tube (glowing of the quartz tube was observed at high powers and low pressures, or when the plasma was not centrally located), and thus, increasing η. Increasing the power increased the plasma diameter (as well as the plasma length), and therefore, increased the heat losses and reduced the efficiency.

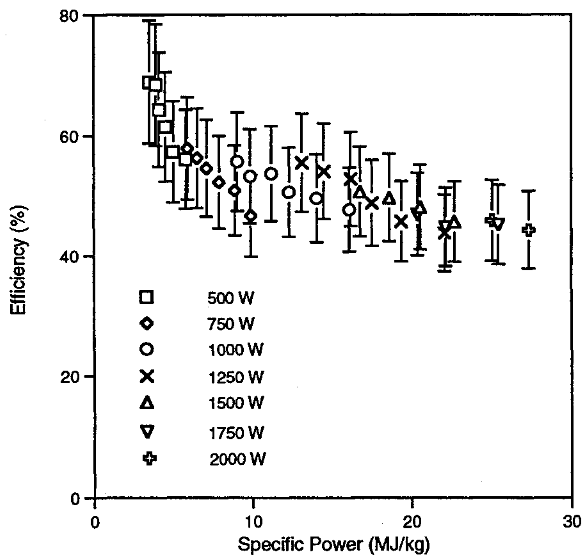

Fig. 5 Overall efficiency as a function of specific power for bluff-body stabilized helium plasmas.

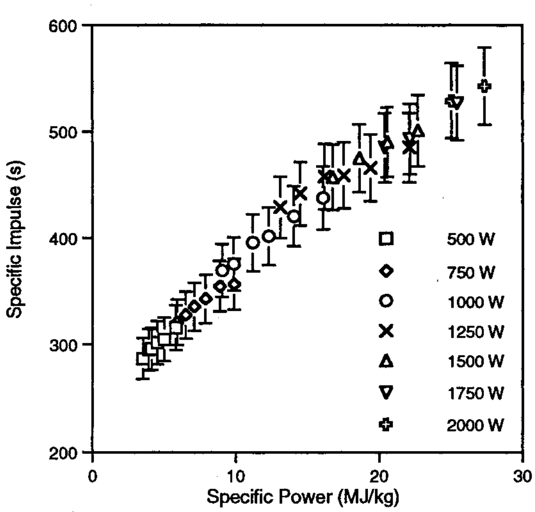

Fig. 6 Specific impulse as a function of specific power for bluff-body stabilized helium plasmas.

Figure 6 shows the calculated I_{sp} vs specific power for bluff-body stabilized helium plasmas. The I_{sp} clearly increases with power and decreases with increasing pressure (and hence, mass flow rate), as would be expected, with a maximum value of 543 s obtained with the present device. The calculated thrust of the system is plotted in Fig. 7 as a function of specific power for different incident microwave powers. It can be seen that the thrust is not a strong function of the input power,

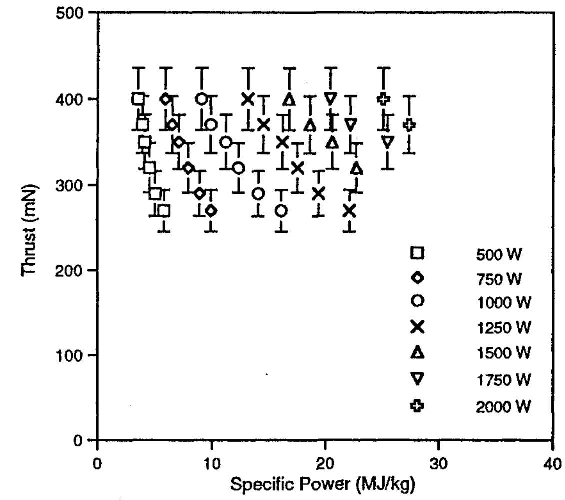

Fig. 7 Thrust as a function of specific power for bluff-body stabilized helium plasmas.

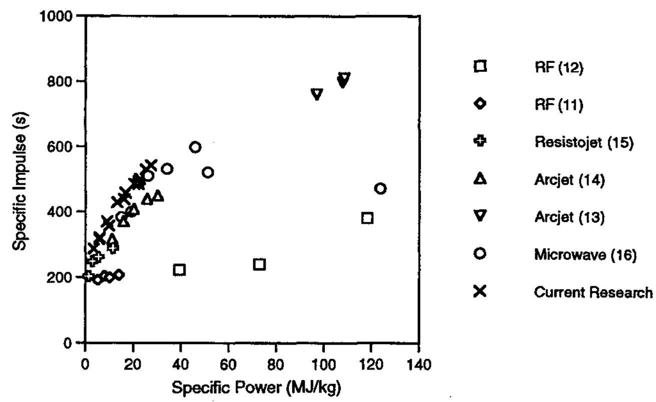

Fig. 8 Specific impulse as a function of specific power for several different electrothermal thrusters.

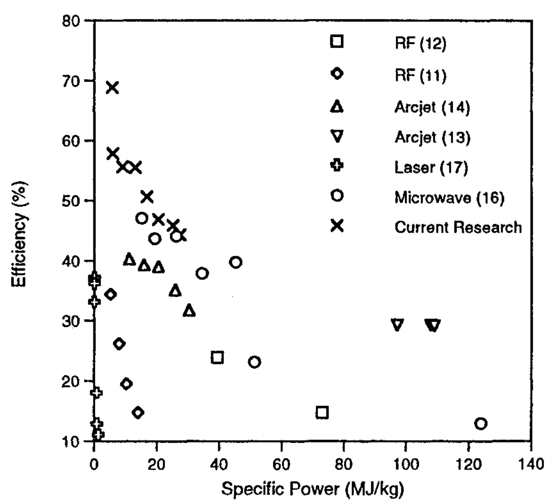

Fig. 9 Overall efficiency as a function of specific power for several different electrothermal thrusters.

and in fact exhibits the same value of 0.4 N at the maximum pressure tested (300 kPa) for each power. The effect of the input power is to change the I_{sp} (and to some extent, the efficiency).

The I_{sp} and efficiencies of several electrothermal systems are presented as a function of specific power in Figs. 8 and 9. It can be seen that at a given specific power, both the I_{sp} and efficiency of the microwave systems are higher than the other electrothermal systems, including the arcjet. It should be clearly noted, however, that the microwave results are based upon calculated I_{sp}, whereas some of the other results shown, such as those for the arcjets, are based upon thrust stand measurements in a vacuum and that the use of helium as the propellant in the current microwave system avoided frozen flow losses. While the calculated I_{sp} for the current microwave system do not include nozzle thermal and viscous losses, chamber thermal losses are included. The absorption chamber used was not designed to minimize thermal losses and a thruster prototype would have significantly reduced heat loss from the chamber.

Spectroscopic Results

The core (peak) T_e for bluff-body stabilized helium plasmas are presented in Fig. 10 as a function of pressure for incident powers of 500, 750, and 1000 W. It is clear that T_e is insensitive to changes in operating conditions, varying from 11,880 to 12,170 K. A slight decrease in T_e with pressure is observed, although the magnitude of this is of the order 200 K, which is smaller than the expected experimental error. The T_e presented here are slightly higher than those previously measured in the TM_{012} mode.[2,4,5] It is believed that this is a result of the difference in experimental systems employed, rather than an actual temperature difference between the two plasmas. The higher quality fused silica optics used for the experiments presented here produced more reliable results than the previously used fiber-optic bundle. The same trend of insensitivity to changes in operating conditions was consistently observed in both cases.

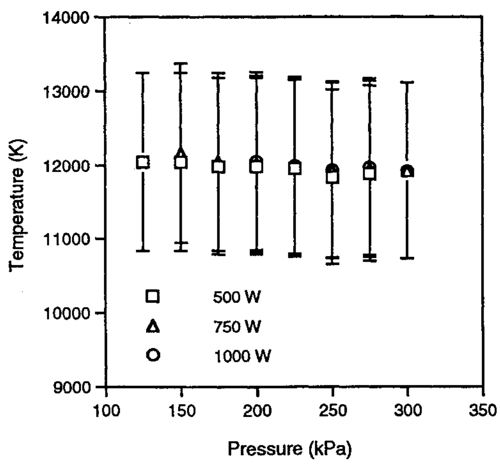

Fig. 10 Peak electron temperature as a function of pressure and power for bluff-body stabilized helium plasmas.

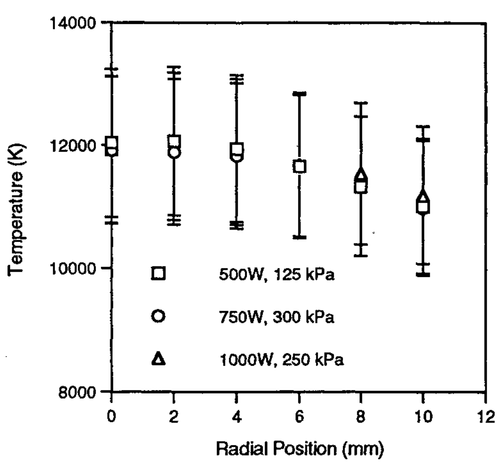

Fig. 11 Electron temperature as a function of radius for bluff-body stabilized helium plasmas.

Using a pair of collimating orifices, a spot diameter of 2.1 mm was obtained, enabling radial profiles of T_e to be determined by using the Abel inversion technique. This spot diameter produces a coarse scan of the plasma, which typically has a diameter of approximately 20 mm, and will result in more reliable results towards the center than towards the edge. The resulting radial profiles are presented in Fig. 11 for a number of combinations of power and pressure, showing that the T_e distributions are extremely flat and insensitive to changes in operating conditions.

Due to the above-atmospheric chamber pressures and relatively low plasma temperature, the electron temperature should be similar to the heavy particle temperature. Thus, these measurements give the temperature of the central plasma "heating element" and show that this temperature does not vary with either gas pressure or microwave power.

Conclusions

Two fluid dynamic techniques, those of bluff-body and swirling flow stabilization, have been used in an attempt to extend the operating limits of the microwave resonant cavity electrothermal thruster. It was found that the bluff-body system is very effective, increasing the maximum power that could be delivered to the propellant gas to the maximum available 2.25 kW. The swirling flow approach was less effective, although this may be a direct result of the geometry of the quartz vessel rather than a limitation of the method itself. With the bluff-body system, it was possible to maintain plasmas up to 500 kPa, and to tune the cavity such that the electromagnetic coupling efficiency varied between 95–100% over a wide range of operating conditions.

The calculated specific impulse and system efficiency varied from 287 to 543 s and 43.8 to 68.9%, respectively, over the range of conditions investigated. The thrust varied from 0.27 to 0.4 N over the same experimental range. These values compare favorably with those from other electrothermal systems currently available or under development. Spectroscopic measurements produced peak electron temperatures of 11,840–12,170 K with very little influence of the operating conditions.

Acknowledgments

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