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CFD MODELING OF MICROWAVE ELECTROTHERMAL THRUSTERS

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Microwave-heated plasmas in convergent nozzles are analyzed using a coupled Maxwell and Navier-Stokes solver to examine relevant issues associated with microwave thermal propulsion. Parametric studies are conducted to understand the effect of power, pressure, and plasma location with respect to the nozzle throat. For nozzles in the 0.5 to 3 N range with helium flow, results show that specific impulses up to 550-650 seconds are possible, with further increases being limited by severe wall-heating. Coupling efficiencies of over 90% are consistently obtained, with overall efficiencies ranging from 40% to 80%. Size scale-up studies–done by scaling the frequency from 2.45 GHz to 0.91 GHz–indicate that plasma migration toward the walls occurs more frequently for the lower frequency. Increasing the cavity aspect ratio and detuning the cavity are found to be effective ways of keeping the plasma on-axis.

Microwave-heated plasmas for space propulsion applications have been considered as an alternative propulsion system since the early 1980's. Like arcjets, microwave thrusters convert electrical energy (in the form of electromagnetic radiation) into thermal energy in a working fluid through a plasma. Unlike arcjets, however, microwave plasmas can be sustained "free-floating" inside an absorption chamber without being attached to any surface, thereby increasing the life of the propulsion system. This has generated considerable interest in determining stable operating regimes and the corresponding thruster performance. Central to this idea is understanding of the strong interaction between the working fluid and the incoming microwave power and the propagation mechanisms of the resultant plasma.

Initial research on microwave plasmas was centered on experimental studies of plasma characteristics at subatmospheric pressures [1,2]. More recent experiments directed toward using the plasma as a means to provide hot gases for propulsive thrust [3-8] have involved higher pressures, typically above one atmosphere. Most of these experiments have dealt with the fundamental characteristics of helium plasmas and the efficiency with which the microwave energy can be coupled to the flowing gas. Stable, free-floating plasmas that are remote from any walls have been routinely observed, but complete propulsive systems have yet to be tested. Companion computational models of the coupling between microwave energy and flowing helium gas have also been developed and validated against experiment [9,10]. In general, the computational trends have supported the experimental findings, showing high coupling efficiencies, proper plasma locations and sizes, and appropriate peak temperatures. These computational efforts have, however, been limited to plasmas in subsonic, unchoked gas flows.

In both the experimental and the computational studies, various coupling methods including resonant cavity plasmas [4,6-9], waveguide-heated plasmas [5,10] and coaxial plasmatrons [3] have been considered. Of these, resonant cavity plasmas appear to offer the best potential coupling method. Cavity plasmas show excellent coupling efficiencies, approaching 100% when some sort of cavity tuning is provided. In addition, they provide good positional stability and long-time operation. In most cases, cavity plasmas are easily positioned on-axis, far away from the walls. Resonant cavity plasmas are, however, not entirely without difficulties in that plasma migration toward the walls has been observed under certain operating regimes. Resonant cavity plasmas that use asymmetrical input-power coupling tend to induce asymmetrical migration toward the walls at higher powers even though they work well at lower powers [4]. This migration can be curbed by switching to symmetrical power coupling, but wall migration is also observed in some applications with completely symmetric microwave geometries. The reason appears to be associated with movement (or expansion) of the plasma from the on-axis maxima in the axial E-field to the toroidal maxima in the radial E-field. By setting the cavity aspect ratio, the relative intensity of the axial and radial electric field maxima can be controlled, enabling more stable on-axis plasma positioning.

Besides controlling off-axis plasma migration by cavity geometry, experimental results have shown that aerodynamic control methods are also effective. Bluff-body stabilization [1,3] and swirled vortical in-flow [7,8] have both been demonstrated experimentally. The effectiveness of bluff-body stabilization has also been predicted computationally, but swirl stabilization has yet to be modeled.

A prototype microwave thruster and the corresponding numerical simulation are given in Fig. 1. The thruster consists of an absorption chamber followed by a standard propulsive nozzle through which the working fluid (helium) flows. The absorption chamber is surrounded by a microwave cavity in which standing E-M waves are established. As the working fluid flows through the cavity, it is heated by a plasma that is initiated near one of the maxima in the standing wave. Although the presence of the conducting plasma distorts the standing wave very severely from its undisturbed mode shape, the original maxima in the field retain their position sufficiently well that the location of the plasma can be controlled quite effectively by the E-M field, and their axial location can be moved by shifting the cavity position with respect to the flow passage. Once the gas has been heated by the plasma, the fluid is expanded through a standard propulsive nozzle to produce thrust.

Typical solutions for a 2.45 GHz helium plasma in a convergent nozzle are shown in Figs. 2 and 3. The temperature contours in Fig. 2 indicate that the plasma is stabilized near the throat by the lower maximum of the electric field standing wave pattern. The forward half of the plasma tends to be hemispherical while the aft section is pulled downstream into the throat by the strongly accelerating flow causing the overall plasma to be somewhat teardrop in shape. The plasma in Nozzle A (right half), which corresponds to a larger mass flow rate, is more compact than that in Nozzle B (left half). This is because, for the larger flow rate, convective effects dominate over thermal diffusion, while, for the lower mass flow rate, diffusive effects are relatively more significant.

Figure 4 shows the calculated Isp's for three nozzle sizes. For the largest nozzle with the largest mass flow rate (Nozzle A), the plasma derives only a small benefit from microwave heating (approximate increase of 70 seconds of Isp over the cold flow regenerative Isp). The two smaller nozzles (B and C respectively) show significant increases in Isp over the cold flow Isp. In these cases, a larger fraction of the propellant gas flows through the plasma and proportionately higher average temperatures are attained. Nozzle C (with the smallest mass flow rate) has the highest Isp ranging from 600s to 630s. For this case, when power is increased beyond a certain level (about 2.75 kW), the Isp is seen to level off due to increased heat losses to the wall. Isp's of this level are attractive for auxiliary propulsion missions.

References

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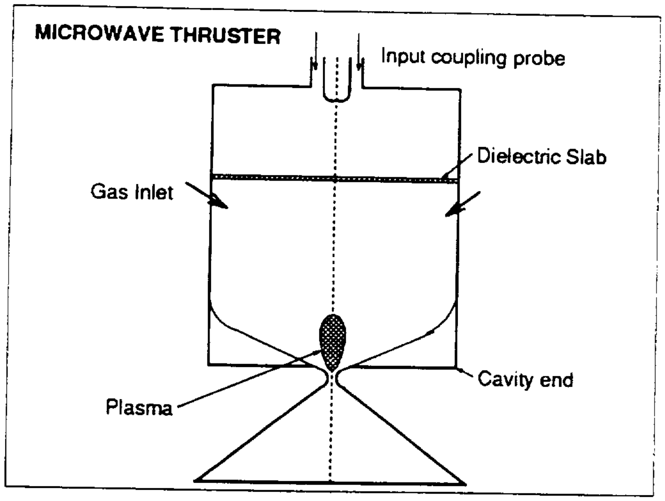

Figure 1: Schematic of a prototype microwave thruster.

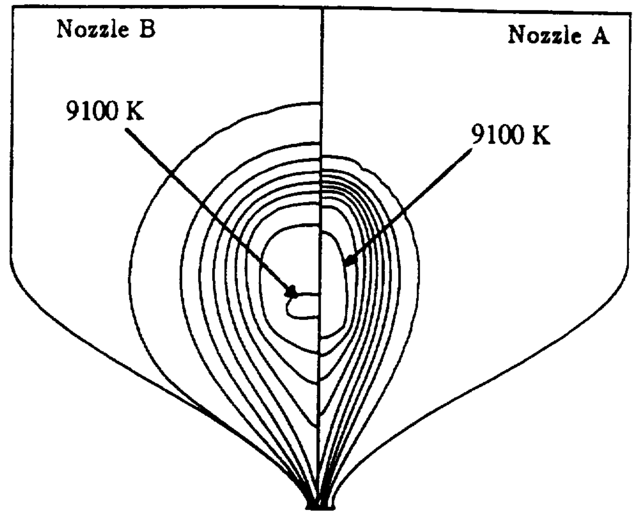

Figure 2: Temperature field for the 1.5 mm nozzle (left side) and the 2.5 mm nozzle (right side). $\Delta T = 1000$ K.

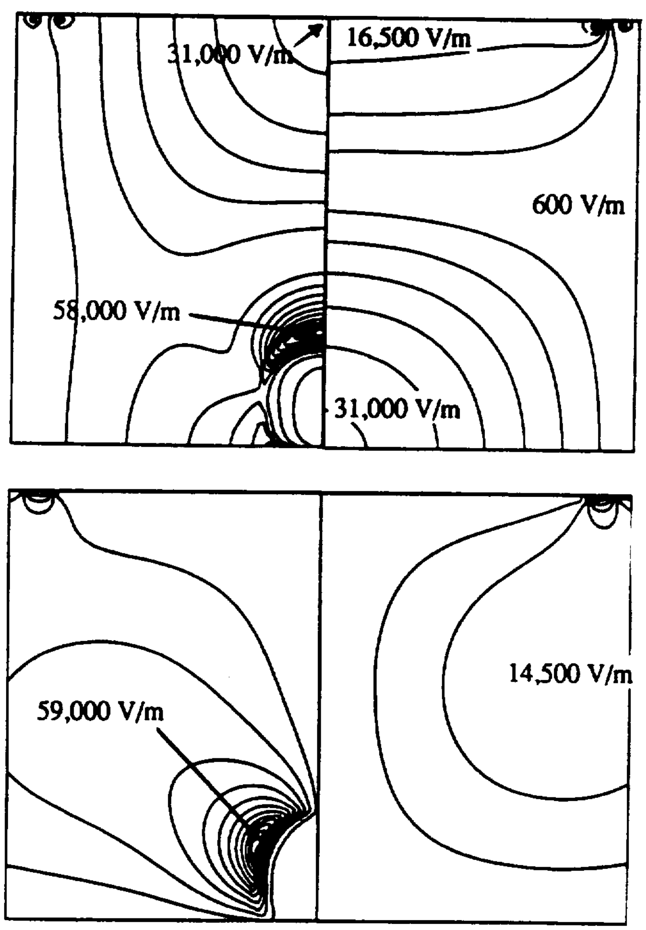

Figure 3: (a) Axial electric field and (b) radial electric field. Left shows electric field distortion due to plasma and right shows undistorted field. $\Delta E = 5000$ V/m.

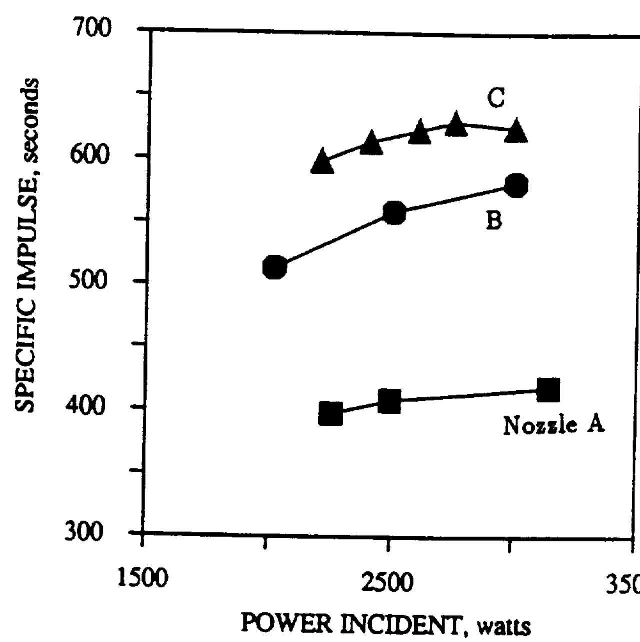

Figure 4: Specific impulse for the three different nozzles at different power levels.