Energy Efficiency Trends in a Coaxial Gun Plasma Engine System

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The efficiency of converting capacitor stored energy into energy in the exhaust stream of a repetitively pulsed two-stage coaxial plasma engine has been determined calorimetrically for various capacitances, voltages, gas densities and density profiles, and gun geometries. Observed efficiency trends have led to empirically determined optimum gun lengths, electrode radius ratios, and energy storage voltages. Energy efficiencies of 63% have been measured so far, without having reached a leveling off of the efficiency increase trend. The largest gains in efficiency have been realized by a new approach to gas pulse injection, which provides more complete filling of the gun barrel with propellant by axial rather than radial injection prior to discharge. The most efficient gun configuration resulting from the calorimetric studies was placed on a thrust balance along with its associated capacitor energy storage system, and thrust data were obtained. Propellant mass flow rate also was measured, and the results were combined with the thrust data to determine over-all efficiencies ($\eta_0 = T^2/2\dot{m}P$) and specific impulses ($I_{sp} = T/\dot{m}g$). The over-all efficiencies, so measured, were typically significantly lower than the energy efficiencies measured calorimetrically, since a large fraction of the injected propellant was not utilized in the discharge. Adjustment of η_0 and I_{sp}, taking into account the unused mass, gave rise to significantly higher η_0 but at undesirably high I_{sp}. Additional steps taken to improve the engine system performance are discussed.

Introduction

THE work described here is part of a continuing long-range program of investigating the operating characteristics and, primarily, improving the efficiency of a two-stage repetitively pulsed coaxial plasma accelerator. Success toward this end resulting from a series of modifications in the electrode geometry and propellant loading characteristics of the second stage of the engine system has been sufficient to warrant a formal presentation of the results even though further improvements remain to be made. In addition, the experiments described here have indicated the relative importance of the various gun system parameters, such as interelectrode propellant distribution, gun geometry, circuit capacitance, and circuit inductance. For ease of identification, accelerators incorporating the successive changes to be described here have been placed in model and mod (modification) number categories.

Increasing the over-all efficiency of a coaxial plasma gun thruster system presents a twofold problem of improving transfer efficiency and improving gun performance. The procedure for improving transfer efficiency probably is understood best in terms of the energy equation obtained from considering the conventional potential equation of the gun circuit

$$Q_0/C = Q/C + iR + (d/dt)[L(t)i] \qquad (1)$$

and

$$\frac{1}{2}\frac{(Q_0 - Q)^2}{C} = \int_0^t i^2R\,dt + \frac{1}{2}\,[L(t)i^2] + \frac{1}{2}\int_0^t i^2\dot{L}(t)\,dt \qquad (2)$$

where

$$L(t) = L_0 + L'x(t) \qquad (3)$$

and L_0 is the inductance of the gun circuit up to the point of current sheet initiation, $x(t)$ is the position of a localized and azimuthally symmetric current sheet in the gun at a time t, L' is the inductance per unit length in the gun, and R is the time constant portion of the gun circuit resistance. (The time-dependent resistance of the plasma is not included in this consideration.) Only two terms describe permanent consumption of energy in Eq. (2),

$$\frac{1}{2}\int_0^t i^2\dot{L}(t)\,dt$$

representing work done on the plasma and

$$\int_0^t i^2R\,dt$$

representing energy lost in heating the capacitor, leads, and the electrodes. It is apparent that L must increase relative to R in order to improve engine efficiency. This may be carried out in several ways: 1) increasing the peak current by decreasing the discharge period, since, under certain assumptions (e.g., according to various current sheet models[2]) L is proportional to i; 2) increasing L by geometrical changes in the gun; and 3) decreasing R by improving the "Q" of the discharge circuit. The first two of these methods were used in the present work. The Q of the circuit (about 7 at 100kc) was determined primarily by the capacitors and could not be adjusted during these studies.

In addition to the i^2R losses included in Eq. (2), parasitic inductance in the gun circuit may lead indirectly to loss of power if, as a result of the initial inductance, the gun circuit is oscillatory. Although, for lack of sufficient data, it cannot be stated conclusively that the initial current sheet always is decoupled from the gun circuit at a point somewhere between voltage zero and current zero at the gun terminals, this has been observed to be the case on the several occasions that

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