Quasi-Steady Plasma Acceleration

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A coaxial plasma accelerator driven by protracted pulses of current in the range of $10^{-6}$ to $10^4$ A amp and synchronized mass flows from 1.0 to 50 g/sec of argon attains, after some tens of μsec, a stable acceleration mode which replicates in every observable detail steady flow self-field magnetoplasmadynamic acceleration. This "quasi-steady" discharge format is characterized by constant terminal voltage and arc current, a diffuse, fixed current distribution within the discharge, and a steady plasma efflux at velocities in excess of $10^4$ m/sec. The device is thus of interest as a simulator of self-field arcjet operation which is much more amenable to detailed diagnostic study, and which can be extended to multimegawatt power levels totally inaccessible to steady flow testing. In addition, it may presage a repetitively pulsed quasi-steady thruster of high-efficiency and variable thrust capability.

I. Introduction

Stabilization of the discharge current patterns of pulsed plasma accelerators into steady diffuse phases for pulse lengths above several microseconds has been demonstrated for several electrode geometries. Study of this "quasi-steady" phase for an electrode configuration resembling the steady state magnetoplasmadynamic (MPD) arcjet is attractive from several points of view. First, such quasi-steady operation permits application of transient diagnostic techniques within the arc chamber and exhaust plume, environments normally too hostile for detailed study in steady flow operation, even at the 100 kW minimum power level required for self-field acceleration. Second, the quasi-steady experiment permits extension of MPD operation to megawatt power levels totally inaccessible to steady experiments because of heat transfer, power supply, and gas handling limitations. Such high-power operation is of basic interest because the over-all efficiency of the MPD arc has been observed to improve as the power level is increased, and may also be instructive for advanced mission studies. For example, certain projections of manned missions to the near planets favor propulsion system power in the range of 1-10 Mw; quasi-steady MPD studies may provide an initial hint on the feasibility of single thruster operation in this range. Finally, the quasi-steady acceleration mode may prove to be an interesting propulsion technique in its own right. In particular, it is possible that intermittent long-pulse operation may combine the benefits of high-power MPD operation with tolerable average power consumption and simple variable thrust capability via duty cycle adjustment.

II. Experimental Design

Proper quasi-steady operation requires rather precise correlation of the injected mass pulse with the applied current pulse. With reference to Fig. 1, the injected mass flow rate, $m$, must rise quickly ($f$) to a steady value, and remain at that value until after the current pulse $J$ has been completed ($f$). The current pulse cannot be initiated until the chamber pressure has reached a steady value corresponding to the injected mass flow rate ($f$), but this time must be sufficiently

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Fig. 1 Characteristic times for current and mass flow pulses.
Fig. 2 Schematic of accelerator electrical and mass injection systems.

the arc chamber with six interchangeable injection tubes connecting the end of the Plexiglas driven section to the discharge chamber. The tube is not operated in the conventional manner in the sense that the driven section is not maintained at a continuum pressure level, but is pumped out to the back pressure of the vacuum tank, less than $10^{-5}$ torr. The driver section is normally pressurized to 35 psia. Upon rupturing the diaphragm, the pressure history at the driven section end wall, and thus the mass injection history, is formed by the superposition of the initial diffuse compression, the rear portion of the initial rarefaction wave which is convected downstream, and the reflection of the rarefaction head off the driver end wall. The tube length is therefore kept relatively short to reduce the time to attain steady end wall pressure. The particular configuration shown, consisting of a driven section 30 in. long X 23 in. i.d., and driven section 6 in. long X 4 1/2 in. i.d., is capable of providing mass flow rates up to 50 g/sec for 3 msec, with a rise time of about 1 msec.

A piezoelectric pressure sensor is mounted in the driven section end wall to monitor end wall pressure time history and to provide a time mark for synchronizing the mass and current pulses. The gas-triggered switch is supplied by a bleed tube from the upstream portion of the shock tube channel. Adjusting the length and size of this line controls the discharge delay time $(r_d)$. Figure 3 shows a typical trace of the end wall pressure history $p_w$ compared with the arc current. In this particular case, the mass flow rate reaches a level of about 36 g/sec after 1 msec. The discharge is triggered at roughly 1.3 msec, a time verified to be sufficiently long to allow the chamber pressure to reach an equilibrium value. Although the capacitor line rings down in a fashion characteristic of its mismatch to the load, only the first half cycle is normally employed in this experiment.

Proper simulation of steady MPD operation also involves replication of the essential features of the arc chamber geometry. Based on the typical configuration of a central, conically tipped cathode, a pierced anode slightly downstream and coaxial with it, and axial gas injection upstream of the electrode gap, there remains only the choice of absolute dimensions on the basis of some appropriate scaling criterion. For this purpose, one might require duplication of the thrust density, which for a given exhaust velocity implies equal power density and mass flux density, or, alternatively, a magnetic interaction parameter might be invoked. Actually, these two approaches yield essentially the same conclusion, by virtue of the relation between the arc current and the total electromagnetic thrust (1):

$$T = \left(\mu J^2/4\pi\right) \ln\left(r_a/r_0\right) + \frac{1}{6} = \rho u$$

where $T$ = thrust, $J$ = total current, $r_a/r_0$ = effective radii of discharge attachment on anode and cathode, $\rho$ = mass flow rate, $u$ = exhaust velocity. That is, for a given exhaust velocity, the thrust density, mass flux density, and power density all scale as $(J^2/4\pi) \ln\left(r_a/r_0\right)$. Presuming the insensitive logarithmic factor to be approximately matched by retaining the same ratio of anode orifice to cathode diameters, the absolute values of these radii should thus be scaled linearly with the discharge current. Since we choose to cover the current range from 4000 to 140,000 amp, compared to the 2000 to 4000 amp range of steady devices, their typical anode orifice radius of 3 in. should here be increased by about one order of magnitude. The selected value of 2 in. actually permits study of substantially higher ranges of thrust density than attainable in the steady accelerators.

The thrust relation (1) is plotted in Fig. 4 in a slightly different form to display the corresponding mass flow rates required to achieve an interesting range of exhaust velocities for these large currents. For the chosen anode radius, these transcribe into mass flux densities from 0.10 to 4.30 kg/m$^2$ sec, a range which overlaps and extends the steady flow range of 0.15 to 2.00 kg/m$^2$ sec.$^{13,14}$

The outer face of the anode is allowed to extend almost to the vacuum tank wall, a radius of 17 in., in order to minimize the anode fall voltage$^{15}$ and to allow full development of the exhaust plume. The 2% thoriated tungsten cathode has a 4-in-diam base and extends 1 in. into the arc chamber. A photograph of the chamber showing the cathode, injector plugs, and part of the anode is shown in Fig. 5.

The assembled chamber and mass injection system are installed in a 3-ft-diam X 6-ft-long Plexiglas vacuum tank described elsewhere.$^{16}$ Before each shot the tank is evacuated.

Fig. 3 Current pulse synchronization with injected mass.

Fig. 4 Relation of current, mass flow, and exhaust velocity for a coaxial plasma accelerator.

Fig. 5 View of accelerator chamber.
ness of the electromagnetic acceleration process should be reflected in a u × B or back EMF component. Second, little is known about the resistive component of discharge voltage at current levels above 10^4 amp. In the past, voltage measurements have been used extensively in steady state experiments to compare arc performance with theoretical acceleration models. Figure 7 displays a typical voltage-current trace for the 17.5 ka pulse and an argon mass flow rate of 3.8 g/sec. The slight drop in the current is due to the time constant of the integrating circuit; larger time constants yield perfectly flat profiles, but have less sensitivity. The sharp drop in the voltage signal at the beginning of the pulse from the applied 10 kv to about 180 v is interpreted as signifying the attainment of thermionic emission by the cathode, since any other mechanism would require substantially higher voltages to support this current density.

Steady voltage traces of this sort are observed over the entire range of current and mass flow operation. As summarized in Fig. 8, these raw voltage data show the general trends of decrease with mass flow, and increase with discharge current anticipated from the electromagnetic thrust model. Precise correlation with any analytical model is difficult because of inadequate knowledge of the various power loss mechanisms acting in the discharge. Specifically, the measured voltage must reflect not only the electromagnetic acceleration process, but also the energy transfer to the electrode surfaces via their respective falls, and the electrothermal energy deposition into the gas stream via joule heating in the body of the discharge, i.e.,

$$V = V_b + V_a + V_c + V_t$$

(2)

where

$$V_i = \frac{\text{electromagnetic thrust power}}{\text{discharge current}}$$

$$V_a = \frac{T^2}{2nJ} = \frac{\mu V^2}{32\pi^2 n} \left[ \ln \left( \frac{r_o}{r_c} \right) + \frac{3}{4} \right]$$

(3)

$$V_c = \frac{\text{power to anode discharge-current}}{\text{discharge current}}$$

$$V_t = \frac{\text{electrothermal power to gas}}{\text{discharge current}}$$

(4)

(5)

(6)

The magnitudes of $V_a$, $V_c$, and $V_t$, and their dependence on $n$ and $J$ are poorly known. It seems reasonable that $V_t$ should be slightly higher than the work function of tungsten,
say ~5 v, a value consistent with certain unpublished electric probe studies of similar discharges in this laboratory. These studies indicate anode falls in the vicinity of 15 v up to currents of 300 ma. The dependence of $V_a$ and $V_z$ on $m$ and $J$, although not carefully studied, appears to be weak.

The electrothermal power input encompasses the ionization of the flow, and all internal excitation, random thermal, and radiation processes which attend it, as well as the joule dissipation associated with passage of the discharge current through the ionized medium. Some of this input may be recovered as useful thrust by electrothermal conversion in the exhaust plume and the remainder constitutes a frozen flow loss: the distinction is immaterial so far as the contribution to the terminal voltage is concerned. It is common practice in estimating the electrothermal voltage to assume that the ionization potential effectively limits the temperature of the particulate species in the plasma, and even to make the approximation that the sole significant energy sink is the single ionization of each incoming particle:

$$V_i = \frac{(m/M)e\xi_i/J}$$

where $M$ is the atomic mass, $e$ the electronic charge, and $\xi_i$ the first ionization potential. A second approximation to this approach inserts a constant factor to cover the excitation, radiation, and random thermal modes that accompany this ionization level. The significant element in either formulation is the linear coupling of $V_i$ to the mass flow, and this feature is clearly denied by our total voltage data. Figure 9 shows the experimental data for $J = 17.5$ ke compared to calculated values of $V_i$, corrected by $V_a + V_z = 20$ v. The difference curve, which must be $V_i$, rather than increasing linearly with $m$, reaches a constant asymptote, $V_i$, implying no further thermal input regardless of the increase in mass flux. Similar behavior is found at other current levels, with $V_i$ increasing linearly with current at a slope of about 4 v/ka, i.e., in this domain the plasma acts as an ohmic medium, with a fixed resistance of 0.004 ohm.

V. Current Density Distribution

Enclosed current contours in the exhaust plume and discharge chamber are mapped with standard magnetic probes of 38 Formvar wire, oriented in the r-z plane. Their integrated signatures present local time histories of the azimuthal magnetic field; cross plotting then yields the spatial distribution of the field at any given time, which, for the observed azimuthal symmetry, is directly proportional to the fraction of the discharge current enclosed by a circle at the given radius. In operation, four probes, mounted on a movable carriage within the exhaust tank, are positioned remotely between each of a sequence of discharges to accumulate the necessary matrix of data. Figure 10 displays typical maps of enclosed current contours in the chamber and near-exhaust for quasi-steady conditions of 1.2, 5.9, and 36.0 g/sec mass flow at a current level of 17.5 ka. As in the luminosity photographs, these figures exhibit characteristics common to the particular nominal exhaust velocity, regardless of the individual level of current or mass flow. First, for the higher velocities, Fig. 10a, the given contours are slightly extended downstream into the plume; for the lower velocities, Fig. 10c, the contours are withdrawn slightly upstream into the chamber. Second, for all quasi-steady conditions observed, no significant amount of current extends farther than one orifice diameter outside of the chamber, either axially or radially. Third, the bulk of the current does not coincide with the luminosity patterns, such as those shown in Fig. 6. This is in contrast to most pulsed plasma accelerators where the luminosity provides a very good indication of the maximum current density location. Fourth, in all gases studied, the current attachment on the cathode completely covers the surface, i.e., the effective radius of attachment for purposes of relation (1) is the maximum material radius. As the nominal exhaust velocity increases, the distribution shifts from a fairly uniform one to one more peaked toward the cathode tip.

VI. Velocity Measurements

To this point, the observed performance of the accelerator has been catalogued in terms of the nominal velocity called out by relation (1) or Fig. 4 for given inputs of mass flow and current. This relation is based on many assumptions of flow and field geometry, of lack of significant electrothermal conversion, and in particular of complete utilization of the injected working fluid, whose validity is not readily assessed experimentally. The last assumption is particularly critical
to the exhaust velocity actually attainable in the accelerator, since any failure of the discharge to accelerate all of the injected flow, or any acquisition of spurious mass from electrodes, insulator, or background gas, distorts the m factor in Eq. (1). For these reasons, experimental determination of the actual velocity field of the exhaust plume is highly desirable. Unfortunately, this measurement, both in steady flow devices and in this quasi-steady version, has proven difficult. Tidious Doppler shift techniques have provided a few isolated data points for the former, but are less applicable here. Exploratory experiments with displaced pairs of biased double electrostatic probes indicate quasi-steady velocities on the accelerator axis of approximately \(2.5 \times 10^4\) m/sec for the \(J = 17.5\) kA, \(m = 5.9\) g/sec combination. A gridless ion energy analyzer returns a similar value for the same conditions. Description of these techniques and more complete presentation of their results appears in another reference. Considering the uncertainties in these measurements, and our lack of knowledge of the remainder of the flow field, they compare reasonably with the nominal value of \(1.2 \times 10^4\) m/sec derived from relation (1), and suggest that in this respect the electromagnetic model has some relevance to the experimental situation.

VII. Summary

By appropriate sequencing of tailored current and mass pulses, a quasi-steady acceleration phase has been achieved in a coaxial geometry resembling the steady, self-field MPD arcjet. Detailed measurements have shown that all pertinent arc processes become steady on a time scale short compared to the current pulse length and that a high-velocity plasma is thereafter continuously ejected from the accelerator. Terminal voltage measurements, Herr-cell photography, and time resolved magnetic field distributions are readily attained, and illuminate certain of the arc acceleration characteristics. In particular, the voltage measurements show a current and mass flow dependence which is not in agreement with estimates based on the ideally anticipated voltage components. Magnetic field measurements show that the stabilized current zone completely fills the arc chamber and covers the exposed cathode surface with a nearly uniform current density. Yet, little of this distribution spreads outside the anode orifice and virtually none extends beyond one orifice diameter either radially or axially. Preliminary velocity measurements confirm operation in a range of exhaust speeds of interest to advanced propulsion.

References


