Abstract

In this paper both theoretical and experimental results are presented that a) demonstrate the effects of electrode geometry on the operation of the magnetoplasmadynamic (MPD) arcjet, and b) describe the "onset" phenomenon not as a single phenomenon but as two distinct phenomena—the first being related to an anode starvation mechanism and the second arising from full single ionization in the plasma bulk. Theory and data both show that the electrode current concentrations can be locally changed by varying the channel's interelectrode separation. The experiment (conducted on a large radius annular geometry) and subsequent theory also show a clear separation between an anode depletion description of onset (caused by the radial component of the thrust vector), indicated by the growth of a large anode voltage drop, and the onset indicated by unsteady large amplitude voltage oscillations which are attributed to a global instability of the electrothermal type occurring near full ionization.

1.0. Nomenclature

A = cross-sectional area
B = magnetic induction
B0 = entrance magnetic induction
D1 = ambipolar diffusivity
E = ionization energy per atom
e = fundamental charge
G = mass flow per unit area
H = interelectrode separation
H0 = entrance interelectrode separation
I = total current
I0 = ionization layer thickness
k = wave number
kB = Boltzmann constant
l1 = inlet layer thickness
m = ion mass
m = mass flow rate
n0 = electron density
n0 = neutral density
n1 = ionization rate
R = gas constant
R0 = recombination constant
S(Te) = (n0/n1)_{equilibrium}
T = mean temperature
T0 = electron temperature
Tt = ion temperature
t = time
u = mean mass velocity
v = terminal voltage
w = channel perimeter
x = axial coordinate
y = transverse coordinate
z = Hall parameter

nu = electron collision frequency

mu = permeability of free space

P = total pressure

r = plasma density

sigma = plasma electrical conductivity

omega = complex wave frequency

2.0. Introduction

Coaxial self-field MPD thrusters need to operate at very high mean power densities for the useful back e.m.f. to exceed the Ohmic voltage drop in the plasma and the near-electrode drops. This high power density guarantees sufficient ionization to put the plasma in the Coulomb-dominated regime. Beyond this point, additional ionization may detract from the overall efficiency since bulk recombination in the nozzle is unlikely. It is therefore important to reduce the local Ohmic dissipation (which feeds the ionization process) to a minimum value as possible within the constraints of providing sufficient magnetic interaction and ionization.

For this reason, it would be desirable to have the ability to specify or control the distribution of current throughout the MPD channel. A uniform current distribution, hypothesized as providing approximately (at least locally) the maximum ratio of mechanical work to total energy input (Ref. 1), might help increase thruster efficiency by reducing frozen losses.

An additional potential benefit of a uniform current distribution is a reduction of localized electrode damage where current normally concentrates, typically the cathode root and the anode lip. However, more needs to be done to verify this point, since, for instance, anode voltage drops in an arcing mode are known to fall as the current density increases.

Operation at these high power densities has also been characterized by a phenomenon known as "onset". At onset, MPD arcjet performance has been seen to degrade rapidly. This limit, characterized by a large increase in terminal voltage accompanied by large amplitude voltage oscillations, has been linked to thruster erosion, decreased thruster efficiency, and unsteady operation.1,2,3 This limit has prevented MPD arcjets from operating at high thrust levels and efficiencies.

Several mechanisms for onset have been postulated. These include anode starvation (Ref. 5), plasma instabilities (Ref. 6), cathode arcing (Ref. 7), and full ionization (Ref. 8). However, they fail to fully describe the observable phenomenology associated with the onset limitation.

These considerations prompted us to develop an approximate design theory (Refs. 9, 10) in which current distribution is an input and channel interelectrode separation then results. Additional
theory was also developed to help understand the phenomenology of onset and provide a guide for its prediction. An experimental program was also conducted to complement the theoretical work at MIT. This paper presents an outline of the theory and the experimental results along with a discussion of their implications.

3.0. MPD Arcjet Design

The reader is referred to Refs. 9 and 10 for a detailed description of the design theory. In brief, the theory details the role of geometry on the distribution of current throughout the MPD channel, and at the same time, provides information on the two-dimensional structure of the plasma. The effect of geometry on the internal distribution of current can be illustrated from a simplified version of Ohm's law written in a single dimension

\[ j = \frac{\mu_0 \omega_a \mathbf{B}}{2} \left( E - \mathbf{uB} \right) \]  

(1)

In the absence of significant electrode falls, the local electric field, \( E \), is approximately the ratio of the terminal voltage to the interelectrode separation, \( V/H \). At the entrance and exit of the MPD arcjet, the back e.m.f. is low due to either low velocity or low magnetic induction. In order to prevent large current concentrations, the local electric field must be decreased. This may be accomplished by increasing the interelectrode separation.

Baksh (Ref. 5) and Ruge (Ref. 3) both showed that the MPD discharge has a two-dimensional structure which cannot be neglected in evaluating the ultimate performance of the discharge. As a result, this model incorporates the appropriate terms detailing the effects of a finite, nonconstant Hall parameter.

The model is based on a magnetohydrodynamic formulation where the basic limitations are: (a) Steady-state, (b) Two-dimensional geometry, (c) Constant conductivity (constant temperature), (d) Constant anode and cathode drops, hence equipotential walls, (e) Neglect of the initial ionization region (which for high values of \( H/m \) is assumed to be small), and (f) Relatively small transverse property gradients. From these assumptions, the MHD equations of motion can be simplified to the following induction equation

\[ \mu_0 \omega_a \frac{\partial \mathbf{B}}{\partial t} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{u} \times \mathbf{B} \]  

(2)

where \( \mathbf{E} \) is the sum of the thermodynamic and magnetic pressures and is independent of the transverse coordinate

\[ \mathbf{E}(x) = \rho RT + \frac{\mathbf{B}^2}{2 \mu_0} \]  

(3)

The term on the left hand side of Eq. (3) is the convection of the magnetic field; the first term on the right is the transverse diffusion of magnetic field, and the second term arises from the nonzero Hall parameter.

Equation (2) is solved in an approximate manner. The approach used started from a zero'th order solution in which an assumed axial electric field cancelled the axial current, thus guaranteeing zero transverse variations. This results in the quantity \( B/\rho \) becoming a convective constant, which enables direct algebraic solution for the various zero'th order flow variables. This solution was then modified by a perturbation scheme which determined the transverse variations created by relaxing the axial field to zero. Within the limitations of the theory, we were then able not only to calculate the flow area variation required for a specified axial distribution of current density, but also to predict the conditions at which transverse density gradients grow to the point of depleting the anode wall.

For the experimental channel, the chosen design conditions were:

- Mass flow rate \( \dot{m} = 4 \) g/sec (Argon)
- Current \( I = 42 \) kA
- Length \( L = 1.9 \) cm
- Throat height \( h^* = 1.9 \) cm
- Current distribution Uniform to zero'th order

Figure 1 shows the theoretically determined channel shape, which can be seen to be convergent-divergent. Figure 2 shows the calculated current streamlines. Notice the presence of axial current, which somewhat distorts the imposed uniform zero'th order current distribution, and is, of course, responsible for anode depletion. Figure 3 shows the variation of the plasma density throughout the channel. Anode depletion is readily observed in this channel, although it only occurs for the specific conditions of this calculation at a small portion channel just upstream of the channel throat.

4.0. Experimental Apparatus

The theory is two-dimensional, but in order to avoid sidewall problems (and to keep with standard design practice), we decided to use a cylindrical geometry, with only minor adjustments in the theory. To reduce the inaccuracy introduced by the cylindrical effects, the mean radius of the device was chosen rather large (6.3 cm). In this geometry, the anode was made purely cylindrical for convenience, with the cathode taking up the required contour. The calculated anode depletion current was only slightly above the design value of 42 kA. For comparison, a form of the theory of Ref. 5, modified for cylindrical effects (see Ref. 10, Appendix B), predicts anode depletion at 41 kA.

For comparison, two other channels were built. One had constant interelectrode separation (constant area channel—CAC), at the same value as the throat of the fully flared channel (FFC), and the partially flared channel (PFC) which had the theoretical contour downstream of the throat, but constant cross-sectional area upstream. In addition, the FFC was built with less drastic upstream area variation than required by theory, because theory itself also indicated levels of dissipation near the entrance would be too low to support rapid ionization of the entering flow. The MPD thruster is shown in Fig. 4 and the three built channels geometries are diagrammed in Fig. 5.

In order to provide for quasi-steady operation, this MPD arcjet is powered by an eight stage inductor-capacitor (L-C) ladder capable of storing 400 J. It has been configured to provide a current pulse of over 60 kA for a duration lasting approximately 300 \( \mu \)s.

The arcjet is situated in a stainless steel vacuum tank 7 m long and 0.6 m in diameter. Six fast acting valves provide a gas pulse from a reservoir directly behind the arcjet channel. Upon command, these valves are fired simultaneously. After an appropriate delay to ensure steady-state flow, the discharge is initiated into an ambient pressure less than 10\(^{-4}\) torr, and the data acquisition system is triggered.

Thruster diagnosis is accomplished primarily by the use of probes. Current is measured by time
integrating the measured magnetic flux, and voltage is measured either by a high impedance differential voltage probe or a floating potential probe. A large Rogowski loop is used to measure the total thruster current and a Tektronix 1000:1 voltage probe is used to measure the terminal voltage. Internal distributions of magnetic field and floating potential are also obtained by probing. The magnetic field is measured from a small 1/16 inch Rogowski loop placed in a quartz tube located directly in the plasma flow. The floating potential is measured by a single Langmuir probe also placed in the plasma stream.

In addition to this probing, spectroscopic emission measurements at the exit plane of the thrusters were made. A 1.26 m Czerny-Turner spectrometer with a Silicon Intensified Target (SIT) digitizing camera at its exit slit were used for this purpose. The experimental setup is shown in Fig. 6. For a more detailed description of the optical analysis, see Ref. 11.

5.0 Results

5.1. Terminal Characteristics and Operating Regimes

Initial tests with the CAC at the nominal 42 kA, 4 g/s of argon operating point showed erratic and often catastrophic ignition. This was attributed to insufficient inlet ionization, coupled with the large non-segmented electrode perimeter. Conditioning by repeated discharges did improve the ignition characteristics, but it is clear that operation with a depleted anode is the result of stronger diffusion of charged pairs (ambipolar diffusion), due to the smaller transverse dimension, which provides for an ionization energy sink. This will be discussed further in section 6.

Thus, these channels clearly separate two types of effects which have in the past been together ascribed to onset. From the efficiency standpoint, it is clear that operation with a depleted anode is unacceptable, but there seems to exist an operational regime between the onset of performance degradation, noted by anode related losses, and the onset of performance degradation by electrode erosion caused by catastrophic arcing.

5.2. Results of Interior Probing

Using the magnetic probes, maps of current streamlines were constructed for the higher currents before arcing onset (some data were also taken at lower currents, but they are less reliable due to the difficulty in guaranteeing a symmetric discharge). Using these data (Fig. 13), one can construct plots of current density along the cathode surface versus axial distance. These are shown in Fig. 14 for all three channels. It is clear that the strong current concentration at the exit of the constant area channel is greatly reduced in both flared channels (PFC, FFC), especially in the PFC. The FFC also shows a reduced inlet current concentration as compared to both the CAC or the FFC, which have a constant upstream separation. The current displaced from this peak is redistributed throughout the rest of the FFC, contributing to the higher level seen downstream when compared to the PFC. These results are in qualitative agreement with theoretical predictions. That the reduction in the inlet and exit current concentrations does reduce overall dissipation is confirmed by electron temperature profiles at the exit plane, as shown in Fig. 15.

A direct comparison between experimental and theoretical current distributions is made difficult by the fact that the data are for a current level higher than the design current. In Fig. 16, we have overlaid the experimental current lines in the FFC at 60 kA (solid lines) and those for a hypothetical channel designed for 60 kA (broken lines). Aside from the slight change in channel contour, and from the greater extent of the outside current "spillage" in the experimental data, there is little correspondence, particularly regarding the slopes of the lines (related to the local Hall parameter).

Two obvious sources of theoretical errors are the presence in the experimental channel of a large and axially non-constant anode drop and the neglect of the initial ionizing region in the arcjet. It can be seen from the equipotential map for each channel, in Fig. 17, that the anode drop is not constant and is maximum near the throat.

6.0. Theoretical Discussion

As noted, no large-scale voltage fluctuations were seen in our tests at current levels well in excess of that at which anode depletion was both predicted and observed (about 35 kA). In fact, for the CAC, there was only a hint of unsteadiness at the highest recorded current (64 kA), while the FFC showed a sharp transition to unsteady conditions only at around 60 kA. There were also indications (Ref. 11) of a high degree of ionization being reached at the high current levels. Turchi has postulated (Ref. 10) that as full ionization is approached, the arc will be forced to erode material from confining surfaces in some unspecified manner in order to strike a power balance, and that this gives rise to the "onset" syndrome. An alternative possibility near full ionization is the occurrence of a fast-growing electrothermal instability; once the ionization energy sink is largely removed,
concentration of current in some area will lead to an electron temperature excursion there, creating a locally greater conductivity and thus reinforcing itself. The resulting current channel will be restricted by heat and particle diffusion to sizes, as we will see, no less than about 1 cm, and will be convected by the flow. Thus the expected voltage signature is a sequence of voltage pulses as the convected current channels disconnect from the open end of the thruster. If this is in fact the observed pattern. It is therefore of interest to analyze both the inlet ionization process, and the subsequent plasma stability in order to compare quantitatively to the data.

6.1. Ionization in the Inlet Region

Considering first a long constant-area channel with a mass flow per unit area, G, one can impose conservation of mass, momentum, and energy between the inlet and the downstream asymptotic state where the condition, \( E = \omega B \) is finally reached. This is to be supplemented with the statements that the asymptotic speed, \( \omega \), must equal the appropriate magnetosonic speed and that smooth sonic passage occurs at some intermediate point (see Ref. 12). Also, if wall losses are ignored for now, the final state is one of Saha equilibrium (\( T_e = T_i \), \( n_i = S(T_e) n_i \)). The resulting set of equations can, in general, be solved for all of the asymptotic variables, such as velocity, magnetic field (hence total current in the initial layer), density, degree of ionization, and the channel electric field, \( E \). However, the solution is simplest if thermal effects are neglected, i.e., \( p \ll B^2/2\mu_0 \) and \( \frac{1}{2} k T_e \ll E_i \), and if the initial speed and enthalpy are neglected compared to downstream values.\(^{12}\) In that case

\[
\begin{align*}
\rho u &= G \\
\begin{bmatrix} G_u + B^2/2\mu_0 & B \theta \\ B \omega & \mu_0 \end{bmatrix} & \begin{bmatrix} B \\ \mu_0 \end{bmatrix} &= \begin{bmatrix} B \\ \mu_0 \end{bmatrix} \\
G (\alpha E_i + u^2/2) + \frac{E}{T_e} (B - B_0) &= 0 \\
E &= \omega B \\
\rho &= \frac{1}{\mu_0} \rho^{1/1} \\
\end{align*}
\tag{8}
\]

where, in Eq. (8), the magnetosonic speed has reduced to the Alfvén velocity. Of these, Eqs. (4), (5), (7), and (8) can be easily solved to give

\[
\rho = \frac{3}{2} \frac{B t^2}{B_0^2} \\
\rho = \frac{B t^2}{2 G} = B_0^2 \frac{G}{8} \\
E = \frac{B t^2}{2 G} \\
B = \frac{B_0^2}{G} (9a, b, c, d)
\]

These are exactly the limiting solutions obtained in Ref. 12. In addition, Eq. (6) now provides an expression for the eventual degree of ionization:

\[
\alpha = \left( \frac{4}{27t^2} - \frac{2}{3} \right) \frac{\mu_0 B t^2}{n(t_1^2)}
\tag{10}
\]

This can be reworked into an "equipartition statement", giving in the asymptotic condition

\[
E_{eq} = 0.4641, \quad \text{which clearly specifies the "frozen loss" penalty to be paid for the kinetic energy gain. This ratio, as we will now show, depends on channel geometry, and is reduced for convergent channels.}
\]

For channels with non-constant area, one further assumption is required in order to obtain simple solutions, namely, high magnetic Reynolds number, such that the initial layer is thin compared to the area variation length. With this, we can again use for \( \rho, u, B, \) and \( V \) (the transverse voltage) the solutions reported in Ref. 12.

Sec. 4.2, and then obtain \( \alpha \) from the energy balance as before. These results are shown in Table 2.

As the table clearly shows, the degree of ionization, and hence the frozen loss penalty, is, for a fixed throat size, strongly reduced when an enlarged inlet cross-section is used. A fairly accurate interpolation formula is

\[
\alpha \approx \frac{1}{1 + 1.0825(\frac{B}{B_0} - 1) + 0.6316(\frac{B}{B_0} - 1)^3}
\tag{11}
\]

While the results so far are rigorously obtained from a well-defined set of equations, they do leave out one potentially significant effect, namely wall recombination losses. A somewhat ad-hoc correction can be made by adding to the energy balance a term representing the loss of ionization energy due to ambipolar diffusion. This term can be approximated by the product of the ionization energy per electron-ion pair times the total rate of ambipolar loss of electron-ion pairs to the walls in the volume defined by the length

\[
L_1 = \frac{2a_{eq}^2}{2B_0 \pi}
\tag{12}
\]

which is a measure of the size of the inlet layer. Using an assumed parabolic transverse profile for plasma density, this gives an additional correction factor for \( \alpha \) of the form

\[
1 + 12 a_{eq} (n_e + n_i) L_1 \frac{a_{eq}}{a_{eq} + 1} \frac{d}{B_0}
\tag{13}
\]

Note that if full return of the neutrals from the walls is assumed, the ambipolar diffusivity can be approximately written as

\[
2a_{eq} \approx \left( 1 + \frac{a_{eq}}{a_{eq} + 1} \right) \frac{d}{B_0} \frac{a_{eq}}{a_{eq} + 1}
\tag{14}
\]

And therefore the product \( 2a_{eq} (n_e + n_i) \) does not vary significantly in the inlet layer.

6.2. Stability Near Full Ionization

For the present purposes, since electron temperature and ionization fluctuations are fast compared to heavy particle dynamics, we can ignore perturbations of \( \rho, u, \) and \( T_i \), while allowing those of \( T_e, \alpha, B \) (or \( C_{eq} \)), and \( E \). We assume wave-like disturbances along \( \delta x \) only, with a basic plasma state that is transversally averaged, but which does show ambipolar losses to the electrode walls. For our conditions, bulk recombination can be shown to be negligible compared to wall recombination, so that a glow-like ionization balance prevails. In the plasma frame, the governing equations are

\[
\frac{\gamma}{\delta t} = \frac{1}{\mu_0} \frac{\partial}{\partial x} \frac{dE}{dx} = \sigma E
\tag{15}
\]

\[
\frac{\partial}{\partial t} + \frac{\partial}{\partial x} \left( \frac{E}{\sigma} \right) = \frac{\partial}{\partial x} \left( \frac{dE}{dx} \right)
\tag{16}
\]

\[
\frac{\partial}{\partial t} \frac{dE}{dx} = -\frac{1}{\mu_0} \frac{d}{\partial x} \left( \frac{E}{\sigma} \right)
\tag{17}
\]

\[
\frac{3}{2} \frac{k_B \frac{\partial^2}{\partial t^2}}{\partial x^2} + \frac{E}{\sigma} + \frac{1}{\sigma} \frac{\partial}{\partial x} \left( \frac{E}{\sigma} \right) = \frac{\partial}{\partial x} \left( \frac{\partial E}{\partial x} \right)
\tag{18}
\]

Here \( R_0(T_e) \sim T_e^{-1/2}, \quad S(T_e) - T_e^{-1/2} = E_i/k_B T_e \).
waves do not propagate, implying that disturbances Eq. (19) shows that the (complex) frequency \( \omega \) to the (real) wavenumber \( k \):

\[
\begin{align*}
\frac{\omega}{\omega_0} &= \frac{9}{8} \times (X - \frac{9}{2}) \left[ 1 - \frac{2\omega}{\omega_0} X \frac{\omega}{2\omega_0 - 1} \right] + \\
&= \frac{k^2}{k^2_c} + \frac{c}{k^2} \frac{X^2 - \frac{1}{2} \omega_0^2}{X^2 + \frac{1}{2} \omega_0^2} \left( X + c \right) \\
\end{align*}
\]

where

\[
\begin{align*}
Q &= \frac{\omega}{\omega_0} \frac{1}{\beta_c} \left( \frac{1}{\beta_c} \right) \\
X &= \frac{X}{\beta_c} \left( \frac{1}{\beta_c} \right) \\
k^2 &= \frac{c}{\beta_c} \left( \frac{1}{\beta_c} \right) \\
\delta &= \frac{1}{\beta_c} \left( \frac{1}{\beta_c} \right) \\
f &= \frac{1}{\beta_c} \left( \frac{1}{\beta_c} \right) \\
H &= \frac{1}{\beta_c} \left( \frac{1}{\beta_c} \right)
\end{align*}
\]

Eq. (19) shows that \( \omega \) is purely imaginary so that waves do not propagate, implying that disturbances are purely convected.

The following conditions are estimated near the inlet for our flared channel tests: \( T_i = 15,600 \text{ K} \), \( T_a = 7000 \text{ K} \), \( \eta_a = \eta_b = 7.2x10^4 \text{ m}^{-1} \), \( \alpha = 0.74 \), \( H = 0.03 \text{ m} \), \( j = 1.25x10^4 \text{ A/m}^2 \). Using \( Q_1 = 5x10^{-15} \text{ A} \), this gives

\[
X = 13.2 ; \quad c = 1.22 ; \quad \delta = 1.58 ; \quad K = 24.9 ; \quad H = 0.051
\]

Since \( c < (X - \frac{9}{2}) = 115 \), collisional damping can be neglected. For the most unstable (longest) wavelength that can be fitted in the 10 cm channel length (assuming a sinusoidal wave with a half-wavelength of 10 cm), \( k = 31 \text{ m}^{-1} \), giving \( k^2 l = 1.81 \), which indicates negligible heat conduction damping. On the other hand, heat conduction becomes significant for half-wavelengths near one centimeter \( (k^2 l = 18) \), which is the same order of the dissipation term), so that shorter waves will not grow.

With the simplifications \( c = k \approx 0 \) the stability threshold \( (q = 0) \) for the longer waves reduces to

\[
\begin{align*}
\alpha &= \frac{9}{2} - \frac{3}{2} \frac{X}{k^2} \\
\alpha &= \frac{9}{2} - \frac{3}{2} \frac{Q}{k^2} \left( \frac{1}{\beta_c} \right)
\end{align*}
\]

6.3. Application to Test Data

Consider first the constant area channel (CAC). Using \( R_b = \mu_0 I / \pi W \) with a perimeter \( W = 0.503 \text{ m} \), Eq. (10) predicts that full ionization is reached at a total current of \( I = 59.5 \text{ kA} \). With the loss correction given by Eq. (13) this is raised to 59.2 \text{ kA} . On the other hand, to be consistent with the approximations used in this analysis, we would expect \( j \) to fall to zero past the inlet layer, so that for currents around 64 \text{ kA} conditions appropriate for instability could at most be reached over very short distances, near the end of that layer. One would, in this case, then expect heat conduction damping to effectively quench growth on such a small scale. The actual current density is not zero (Fig. 14), but, although its precise value is difficult to pinpoint (due to experimental scatter), we do expect it to be substantially less than in the flared channels; in addition, \( H \) is also smaller than in the FCC, and so the non-dimensional dissipation \( \delta \) (Eqs. 19 and 20) is smaller (by \( 5 \text{Y}^2 \)), and thus requires closer approach to full ionization (higher current) for instability.

Turning to the fully flared channel, we need now to use both correction factors, Eqs. (11) and (13) for calculating the ionization after the initial layer. The electron temperature in that region is estimated by equating local ionization rate to ambipolar loss. The local current density is calculated by uniformly distributing the total current. An iterative calculation involving also Eq. (21) then leads to these predicted conditions for the stability threshold:

\[
\alpha = 0.735 ; \quad I = 63.35 \text{ kA} ; \quad T_i = 15,630 \text{ K}
\]

The threshold current compares quite well with the value observed in the tests. It must be noted, however, that the theory is still somewhat crude, and that there is significant uncertainty in the modeling, for example, of the diffusion loss rate, which plays a crucial role in the stability threshold determination.

7.0. Conclusions

Several effects of area variation have been experimentally documented, and the predicted reduction of dissipation at inlet and exit due to a convergent-divergent geometry has been confirmed, at least qualitatively. Anode depletion was noted near the current level predicted by a modified form of Bakht's theory, but a stable region of post-depletion operation was also observed, terminating in large scale instability in the case of the flared channel. On the basis of simplified theory, it is argued that electrothermal instability associated with near full ionization can be the cause of this last phenomenon. If so, our tests would have confirmed both competing theories of onset (based on anode depletion and full ionization, respectively). Interesting design guidelines may follow from the reality of both effects, i.e., the designer would strive to force them to coincide so as to maximize the useful operating range. More detailed work needs to be done, however, to verify or disprove these interpretations.

8.0. References


a) Constant Area Channel (CAC)

b) Partially Flared Channel (PFC)

c) Fully Flared Channel (FFC)

Figure 5: Three Electrode Geometries

Figure 7: Thruster Voltage as a Function of Total Current for an Argon Mass Flow Rate of 4 g/s

Figure 8: Variation of the Voltage Drop from the Anode to a Point Two Millimeters from the Anode as a Function of Thruster Current in the Fully Flared Channel for an Argon Mass Flow Rate of 4 g/s

Figure 6: Orientation of the MIT/MDA Experimental Facility
Figure 9: Radial Profile of the Electron Density at the Exit of the Fully Flared Channel at 60 kA for an Argon Mass Flow Rate of 4 g/s as a Function of T'/T.

Figure 10: Oscillatory Voltage Trace

Figure 11: Variation of the Anode Voltage Drop and the Voltage Rash as a Function of the Thruster Current in the Fully Flared Channel at 60 kA for an Argon Mass Flow Rate of 4 g/s

Figure 12: Variation of the Voltage Rash as a Function of Current in the Three Channels at 60 kA for an Argon Mass Flow Rate of 4 g/s

Figure 13: Enclosed Current in the CAC, PFC, and FFC at 60 kA for an Argon Mass Flow Rate of 4 g/s
Figure 14: Cathode Current Density Distribution for Each Channel at 60 kA for an Argon Mass Flow Rate of 4 g/s

Figure 15: Transverse Variation of the Electron Temperature at the Thruster Exit Plane at 60 kA for an Argon Mass Flow Rate of 4 g/s

Figure 16: Experimental and Theoretical Enclosed Current Contours in the Fully Flared Channel Based on Experimental Data at 60 kA and an Argon Mass Flow Rate of 4 g/s

Figure 17: Floating Potential Contours in the CAC, PFC, and FFC at 60 kA for an Argon Mass Flow Rate of 4 g/s
<table>
<thead>
<tr>
<th>Region</th>
<th>Constant Channel (Volts)</th>
<th>Partially Flared Channel (Volts)</th>
<th>Fully Flared Channel (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>36 ± 15</td>
<td>25 ± 20</td>
<td>16 ± 55</td>
</tr>
<tr>
<td>Plasma</td>
<td>43 ± 30</td>
<td>67 ± 40</td>
<td>82 ± 85</td>
</tr>
<tr>
<td>Anode</td>
<td>64 ± 15</td>
<td>75 ± 20</td>
<td>82 ± 30</td>
</tr>
<tr>
<td>Total</td>
<td>143 ± 5</td>
<td>168 ± 9</td>
<td>160 ± 25</td>
</tr>
</tbody>
</table>

Table 1: Experimental Midchannel Potential Variation for Each Channel By Region

<table>
<thead>
<tr>
<th>( \frac{H_0}{H^*} )</th>
<th>1</th>
<th>1.1654</th>
<th>1.2991</th>
<th>1.5034</th>
<th>1.8520</th>
<th>2</th>
<th>( \rightarrow \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{4E_i \mu_i^i (m_i/m^*)^i}{m_i H_0^i} ) ( \alpha )</td>
<td>0.10313</td>
<td>0.08631</td>
<td>0.07481</td>
<td>0.06049</td>
<td>0.04330</td>
<td>0.0380</td>
<td>( \frac{0.1756}{(H_0/H^*)^i} )</td>
</tr>
</tbody>
</table>

Table 2: Ionization fraction immediately after the inlet current concentration. Note \( H_0 \) is the inlet height and \( H^* \) is the throat height.