Dynamic Voltage-Current Characteristics of a Megawatt MPD-ARC Thruster

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The dynamic voltage-current characteristic of a hot cathode, megawatt (Mw), pulsed MPD-ARC thruster are given for various axial magnetic fields (1.0–2.0 T). The arc is powered by a crowbarred capacitor bank, and the transient data is obtained for the 100 μsec period after crowbar time. Each shot shows a positive sloped characteristic. A series of these dynamic characteristics, spanning 2–14 ka, along with estimated static characteristics are given for argon and for nitrogen propellant. As the magnetic field increases, the dynamic curves tend to be more identifiable as part of a connected, positive sloped line.

Introduction

IN this report the experimental investigation of the voltage-current (*V-I*) characteristics of an MPD-ARC thruster is extended to the Mw power level. The *V-I* characteristic is one of the gross physical characteristics that would help to classify this thruster. This classification is made prior to comparing the thruster to other similar arcs or to examining the detailed physics of the discharge. The *V-I* characteristic is of importance to the power conditioning designer. It is used to properly analyze and design impedance matched and electrically stable power supply-arc systems. One can find described in the literature[1–6] various negative sloped and various positive sloped static *V-I* characteristic curves for MPD-ARC thrusters (or plasma accelerators). These references describe thrusters with power levels of tens of kw or lower. The arc with this geometry and auxiliary magnetic field has gross *V-I* characteristics that range from that of simple, low-current (100 a or less) arcs to that of the more complicated, magnetically confined, annular, high-current [kiloamperes (ka) or more] arcs. Direct comparison of the data of the references with the data of this report cannot be made, because the data of this report is taken at orders of magnitude higher power levels.

This was a short duration experiment and arc *V-I* characteristics are frequency sensitive, so care must be taken in interpreting the transient data gathered in the experiment. This was brought out in Ref. 7, which described the same pulsed apparatus but employing nitrogen propellant. In that report distinctions were made between static, dynamic, and transient characteristics based on definitions described in Ref. 8.

In Ref. 9, *V-I* characteristics of a somewhat similar accelerator are discussed for Mw and even higher power levels. Since that experiment does not employ an auxiliary magnetic field (only its self-field), simple comparisons of results are not possible.

In this report the dynamic *V-I* characteristics of a pulsed, hot cathode, Mw, MPD-ARC plasma accelerator (or thruster) are described for two different propellants and for various magnitudes of auxiliary magnetic field.

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Apparatus

Capacitor Bank

The plasma source was energized by a 10 kilojoule bank which had a resistance of 3.8 milliohms (mΩ) and inductance of 14 nh, and a capacitance of 24.2-μf. Eleven GL-7703 ignitrons, switched synchronously, connect the bank to the source. The equivalent circuit of the bank, crowbar, and source is shown in Fig. 1. Additional inductances were inserted to utilize an existing crowbar switch and still provide a nonoscillatory, truly-crowbarred current waveform to the arc source. After the bank switches were closed, arc current was allowed to develop to its peak current. This takes 21 μsec. Then the crowbar switch was closed, forcing the arc current to decay monatonically with time. The decay time ranged from 250 to 350 μsec, depending on arc resistance. This allowed an almost linear decay of arc current for about 100 μsec after crowbarring, and it is during this period that the data was gathered.

Plasma Accelerator

The arc chamber is hidden from view at the center of the toroidal dewar for the superconducting magnet. The magnet is used to supply the auxiliary magnetic field for the accelerator. Plasma flows to the right from the accelerator into an evacuated glassware system.

Prior to operating the source, the magnet dewar is filled with liquid helium and after it is cold, the magnet wire becomes superconducting. Then the magnet is charged to a given magnetic field setting (0-2.2 T) and maintained at that condition for the testing period. The capacitor bank is charged next. It is not switched until the cathode is heated to temperatures causing 50-a emission and propellant has properly filled the arc chamber.

Argon propellant is introduced into the arc chamber by a high-speed gas valve that is actuated by an electromagnetic

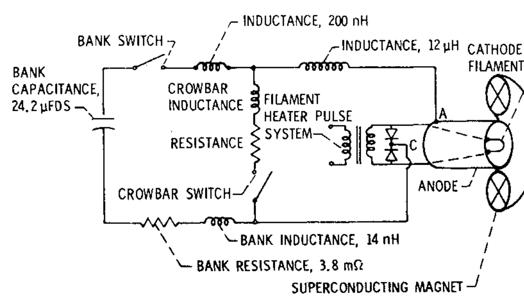

Fig. 1 Equivalent circuit.

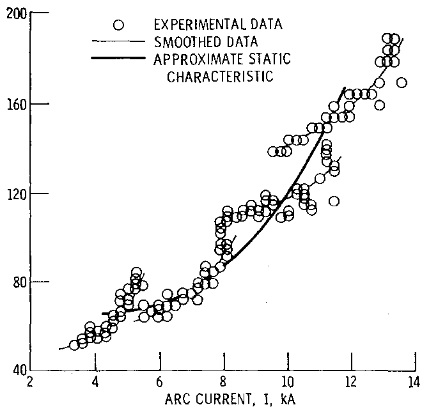

Fig. 2 Voltage-current characteristics (1.5 g/sec Ar, 5.1 T).

hammer system. All tests were run at various flow rates; 1.5, 6.0, or 7.0 g/sec, argon or nitrogen. The transient, cold flow, gas pressure in the arc chamber was measured by a piezoelectric pressure pickup in a previous experiment. Using that pressure and orifice equations for steady flow, the mass flow rate for all the tests of this report were calculated. From the transient pressure records it was found that stable flow occurred after 615 μsec, and the arc was started at that time.

The cathode is an electrically heated tungsten ribbon filament measuring 1-cm wide, 2-cm long, and 1-mm thick. The anode is a 4.2 cm inside diameter copper ring.

A sequence controller controls filament heating time, gas puff injection, delay for gas distribution, bank switch closure, crowbar switch closure, and then data gathering "start" and "stop" times.

An arc plume is formed between the cathode filament and anode ring. The combined action of streaming gas, magnetic field, and arc plume produces a transient plasma flow of a few hundred μsec into the evacuated region.

Instrumentation

Transient arc voltage measurement was accomplished with commercially available resistive divider probes and amplifiers. The signal was sent to a transient digital recorder[10] in a nearby screen room. Dual-voltage probes were used, one on the cathode (position C on Fig. 1) and one on the anode

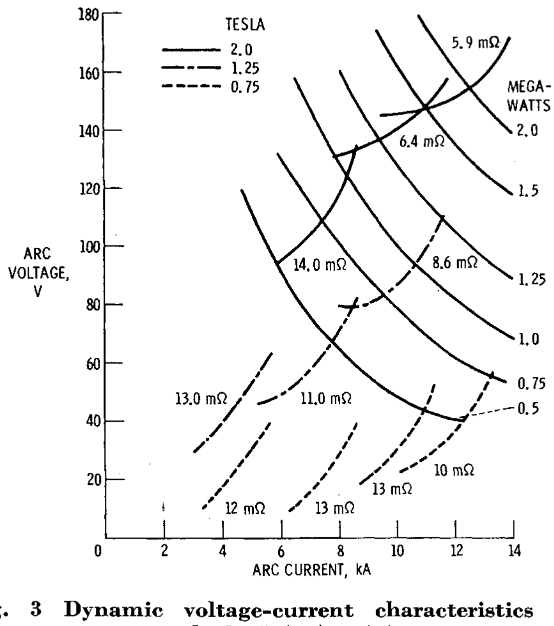

Fig. 3 Dynamic voltage-current characteristics (hot cathode, 1.5 g/sec Ar).

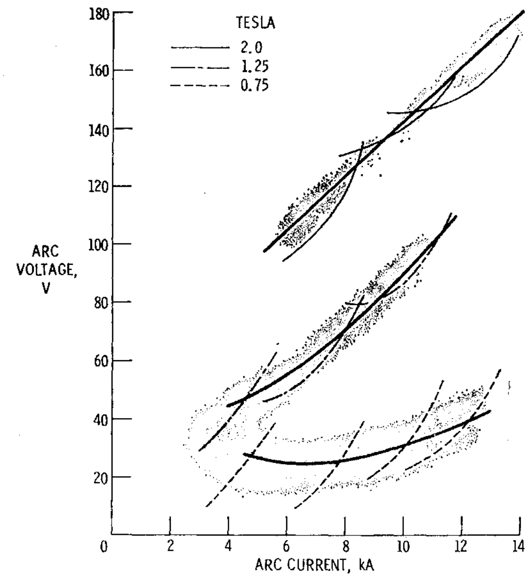

Fig. 4 Estimated static characteristics (hot cathode, 1.5 g/sec Ar).

(position A on Fig. 1), and their signals were electrically subtracted by a difference amplifier, and recorded. The dual-probe technique electrically subtracts the unwanted common-mode signal portion from the "read" voltage signal.

Source current was measured by a precision dynamic current transformer and recorded on the other channel of the transient digital recorder.

The current and voltage signals were digitized every 1.65 μsec after crowbar time, processed in the laboratory computing system, and V-I plots such as Fig. 2 were obtained. During the data gathering time the current is decaying almost linearly with time from its peak value to 80% of peak value. Each curve of Fig. 2 is a separate shot. The highest current data point of each curve is closest in time to the time of crowbar, and, each curve is about 80- to 90-μsec test duration. The mass flow rate was held constant for each shot. The peak current was varied by changing the initial bank charge. For a fixed magnetic field, a series of four different initial bank charge shots were used to cover the range from 2 to 14 ka arc current.

Results and Discussion

Figure 2 shows the data gathered in four typical shots (data points) and least-squares method[11] smooth curves through the data points. The data points show the data spread in one shot as well as the resolution of the digitizer. The resolution is 5.00 v on the ordinate and 250 a on the abscissa for this particular shot. The data shows a positive sloped, curvilinear trend. To understand more fully whether each curve is typically a transient, or a dynamic, or a static curve, more curves must be examined over the full range of arc currents.

Figure 2 shows the data and smoothed curves for four separate shots, each with a different peak current (corresponding to a different initial bank changing voltage). Each curve is for the same mass flow rate and magnetic field. Each curve is a dynamic characteristic about some point on the static V-I characteristic curve. For simplicity, an approximate location of the static characteristic curve has been chosen through the midsection of the family of dynamic characteristic curves. At most this could produce a 25-v error or shift in the curve. The heavy curve shows the approximate location of the static characteristic.

Figure 3 shows how these families of smoothed dynamic characteristics vary with magnetic field for the 1.5 g/sec

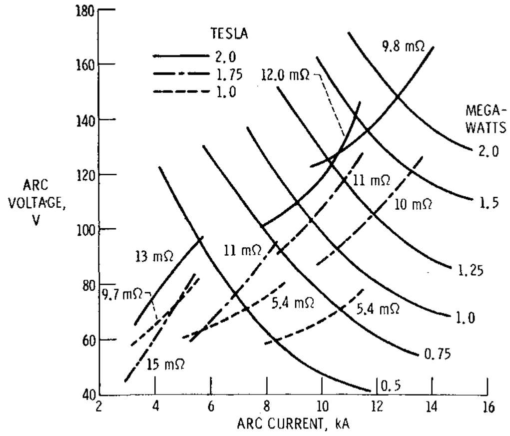

Fig. 5 Dynamic voltage-current characteristics (hot cathode, 6.0 g/sec Ar).

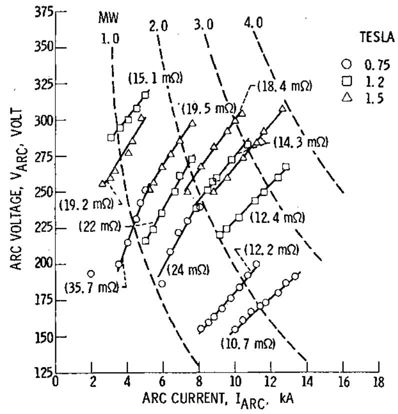

Fig. 7 Dynamic voltage-current characteristics (hot cathode, 7.0 g/sec N_2).

argon mass flow rate case. The dynamic characteristics are curvilinear and positive sloped.

The arc voltage level increases markedly with increasing magnetic field for a corresponding current shot. This is most evident at the higher peak current shots.

In Fig. 3 equal power contour lines have been added to show the power range for each of the families of dynamic characteristics. For the 2.0 tesla magnetic field case, a peak instantaneous power of 2.5 Mw is attained with a 14-ka arc current. The mean dynamic impedance is also shown for each dynamic characteristic. Each of these is the slope of the mean line through each dynamic curve.

The same dynamic characteristics are shown in Fig. 4 with each family enclosed by a shaded area. Somewhere in this area lies the static characteristic along which the family of dynamic characteristics has been generated. An estimated static characteristic curve (double-lined curve) has been shown for each family. As magnetic field increases the slope of the static characteristic becomes more positive.

The 0.75-tesla family shows mean slopes much different than the slope of the static characteristic. This is evidence of time lags in arc plasma development caused by the combination ionization delays[8] and various onset times for micro-instability and plume development. As the magnetic field is increased to 2.0 tesla, the mean slope of the dynamic curves approaches the slope of the static characteristic. That is, in the time duration (80-100 μsec) of this experiment, it is possible to approach static characteristic curves. The effect of the high field is to reduce the time lags in the arc plasma processes. High-current arcs without auxiliary magnetic fields have been found to have positive-sloped static characteristic curves. The positive sloped static characteristics of this report are thus not unexpected. The value of these results lie in 1) the scaling knowledge obtained for high-power MPD-ARC thrusters, 2) how the slope of the static characteristic curve can be adjusted by the magnetic field, 3) noting how magnetic field and arc current combine to provide Mw level power increases, and 4) how a family of dynamic characteristics can be interpreted to give estimated static characteristics as well.

A somewhat similar set of data was gathered for a higher mass-flow rate case (6 g/sec Ar) and is shown in Fig. 5. The slope of the estimated static characteristic of curve for the 2.0 T case is about 8.0 mΩ. This is compared to the 9.3 mΩ for the low mass flow rate. Correspondingly, the power level is generally lower for this case than the 1.5 g/sec set of Fig. 3. The same general comments apply to Figs. 5 and 6 as for Figs. 3 and 4, respectively.

Somewhat different experimental results are noted if the propellant used is nitrogen. Figure 7 is for the same geometry arc but with nitrogen propellant. This is the data described in Ref. 7. Although the dynamic characteristics are all positive sloped, each curve is at much higher voltage than for argon at corresponding current and magnetic field. Also, the estimated static characteristics shown in Fig. 8 do not become positive sloped with the highest fields as they do for the argon flow cases. The power levels (Fig. 7) show that almost twice as much power can be developed in the nitrogen case (7.0 g/sec) as for the corresponding argon case (6.0 g/sec). The dynamic impedances are generally higher for nitrogen also.

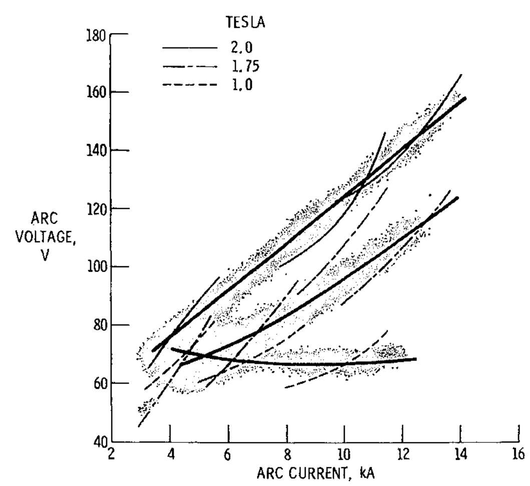

Fig. 6 Estimated static characteristics (hot cathode, 6.0 g/sec Ar).

Concluding Remarks

The dynamic current-voltage characteristic of a hot cathode, Mw level, MPD-ARC plasma source are given for various magnetic fields (from 0.75 to 2.0 T) and two different

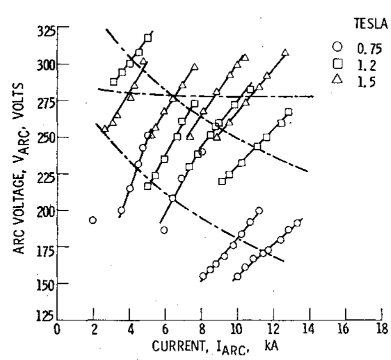

Fig. 8 Estimated static characteristics (hot cathode, 7.0 g/sec N_2).

propellants, argon and nitrogen. The *V-I* characteristics show positive sloped curvilinear characteristics for a power level ranging from 0.25 to 4.0 Mw. For magnetic fields in the range from 0.75 to 1.25 T the pulse duration of the experiment is not long enough to allow static characteristics to develop for either propellant in this geometry.

For magnetic fields in the range from 1.5 to 2.0 T, the pulse duration is long enough to allow static characteristics to develop for argon. As the field increases (1.75-2.0 T) the characteristic curve slope increases and the characteristic curve is linear (slope of 9.3 mΩ for 1.5 g/sec, 8.0 mΩ for 6.0 g/sec).

The positive slope is a characteristic of both static and dynamic characteristic curves at 5–15 ka for argon. The estimated static characteristics show high-current characteristics as well as somewhat-harder-to-estimate "near minimum voltage" characteristics at 2–4 ka. In simple, low-current arcs, ionization lags are responsible for producing dynamic *V-I* characteristic curves. In this report, time lags in arc plasma processes seem to be evident at lower magnet fields, but at above 1.5 T the effect of the auxiliary magnetic field is to decrease the lags. Probably the increased cyclotroning in the arc chamber provides the energy and mixing to reduce ionization lags and give the system more resistance-like characteristics. It has not been determined whether ionization lags or plume development time lags or the combination of these lags is responsible for the observed phenomena. For the experiment times of this report no "spoking" has been observed. Thus the differences in dynamic characteristics cannot be attributed to effects caused by the onset of that instability.

For nitrogen propellant, even though almost double the power is developed than for corresponding argon case, the time lags in arc plasma processes are more evident, in that even at highest field cases the static characteristics are not obtained during the time of the experiments (100 μsec).

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