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Pressure Measurements in the Exhaust of a Pulsed Megawatt MPD Arc Thruster

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Theme

TRANSIENT exhaust pressure history is measured. The variation of the pressure pulse detected in the exhaust with source parameters and duct position is described. How this pulse affects the understanding of the thrust mechanism is discussed. The sequence of events at a given station in the exhaust is experimentally determined using pressure probes, Rogovsky loops, Faraday cup probes, and earlier obtained plasma light and Thomson scattering data.

Content

In the literature on MPD-Arc thrusters, distinctions are made between starting transients, quasi-steady conditions, and steady, d.c. like, operation. These distinctions are important because the dominant physics of the processes might well be different for each case. Most investigators have not examined the starting transients of MPD Arc thrusters. It has been assumed that quasi-steady operation (equivalent to steady operation for much of the pulse time) could be achieved in a time of the order of 10^{-5} sec. This assumption seemed to be justified by experimental observations, plasma light, probe traces, or terminal characteristics that appeared to be quite steady, at least for the 100 μ-sec time periods or so described in Ref. 1.

In this paper, results of transient pressure measurements in the exhaust are presented. The time-varying nature of exhaust pressure is discussed. The significance of these and other measurements for understanding the physical processes in high power MPD-Arc thrusters is evaluated.

The thruster was energized by a 10 kjoule capacitor bank that was crowbarred at peak current to provide a monatonic decay of arc current for 500 μsec. A superconducting magnet is used to supply the auxiliary magnetic field for the accelerator. Details of the arc chamber and an iron filings map of the magnetic field are shown in Fig. 1. Plasma flows from the thruster into a 15 cm i.d. evacuated glassware system. Nitrogen propellant was introduced into the arc chamber by a high-speed gas valve. All tests were run at 7 g/sec nitrogen. After arc initiation, a transient plasma flows for a few hundred microseconds into the evacuated glassware section. The cathode is a tungsten ribbon measuring 1 cm wide, 2 cm long, and 1 mm thick. The anode is a 4.12 cm i.d. copper ring.

The design and response of unique high performance transducers for this application has been reported.[2] This probe concept utilizes a piezoelectric ceramic element supported on a structure of backing rod in an insulated housing. Based on earlier investigations of the discharge environment two probing units were fabricated, both using PZT-5A (Clevite Corp.) piezoceramic: a low-frequency, high-sensitivity probe with sensing surface 1.25 cm in diameter, o.d. 1.9 cm, 60 μv per N/m^2 output, and 2.5 μsec risetime; a high-frequency, low-sensitivity unit with 0.64-cm sensing diameter, 1.25 cm o.d., 15 μv per N/m^2 output, and 0.4 μsec risetime. In each case the sensing surface was electrically insulated by a thin layer (0.1 cm) of epoxy with a definable signal delay time of 0.2 μsec. With such devices, reliable pressure waveshape reproduction could be expected for about 100 μsec after the initial pressure wave occurrence. Thereafter, thermal and acceleration effects made interpretation difficult with the present probes. A glass tubing enclosed Rogovsky loop, with 2.5-cm-i.d. sensing area, was used to measure gross currents flowing in the discharge that threads the loop. A Faraday cup probe was used to collect ions from the streaming plasma. It was biased so as to repel electrons.

The low frequency piezopressure probe was used to measure "cold" gas flow in the duct. Specifically, at arc initiation time the total pressure magnitude on axis at a distance downstream from the anode face of 5 cm (Z = 5 cm) is 340 N/m^2, while farther downstream, on axis, at Z = 30 cm, the total pressure sensed is 6 N/m^2.

Figure 2 shows typical 5-trace overlays of the total pressure signals for the 20.0 ka peak arc current case. The probe signals all show one common feature, the total pressure appears as a single pulse, 18 to 20 μsec wide, with a lower order of magnitude pressure thereafter for 50 μsec. Data to be discussed later in this report will only describe this initial pressure pulse. The impulse provided by the thruster for this period of time is dominated by this pulse. If the transient pressure component of the exhaust impulse dominates over the steady "blowing" component, the total impulse cannot be considered a steady or quasi-steady thrust condition. This is the case for the megawatt-level pulses studied

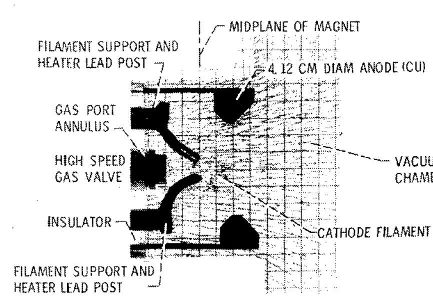

Fig. 1 Arc chamber.

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Index categories: Electric and Advanced Space Propulsion; Plasma Dynamics.

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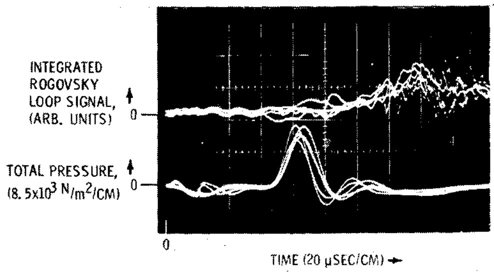

Fig. 2 Typical total pressure and Rogovsky loop traces. 5-Trace overlays for 20.0 ka, 1.0*T* case (Rogovsky loop *r* = 4 cm, *Z* = 25 cm and pressure probe at *r* = 0, *Z* = 25 cm).

in this paper. Much longer powering times will have to be used to insure steady thrusting is the dominant condition.

The other set of simultaneous traces in Fig. 2 show Rogovsky loop signals at the same Z location. These signals provide an indication of the gross current in the plume that extends out from the thruster. The point to be noted here is the fact that the plume current occurs over 20 μsec later than the pressure pulse.

The dominant pressure phenomenon in the exhaust for the first 100 μsec is the narrow transient total pressure pulse. The second most important observation relates to the sequence of events occurring in the exhaust at a particular station. At these power levels, no spokes are noted in the current plume. Rogovsky loops, Faraday cup probes, pressure probes, and results described in an earlier paper[3] on laser scattering diagnosis of the exhaust were used jointly to determine this sequence of events. Within the limitations of the several instruments used in gathering the data, the sequence of events at a particular station can be summarized as: 1) exhaust light arrival; 2) narrow total (and static) neutral pressure pulse, arriving a few microseconds later; 3) ion arrival, or plasma arrival, tens of microseconds later; 4) plume currents initiating at about the same time as 3; and 5) decaying plasma conditions after 3.

This sequence is much like that which occurs in a transient plasma gun. However, such guns have higher velocity current sheets (or plumes) and better structural plume definition. In the present case, it can be anticipated that arc initiation creates a blast or shock wave which propagates in the cold gas that has streamed from the arc chamber prior to ignition. Clearly, the amplitude of such a pressure pulse will depend on the size and pumping capacity of the exhaust duct system. However, even in the largest existing exhaust systems, a distributed cold gas cloud will exist between the source (anode) station and the normal downstream measuring station ($\approx$30 cm) for high mass flow rates (>5 g/sec) generally used. So, in that case, a pressure pulse can also be expected to be observed. Also, the later occurring current plume may act as a plow pushing neutral gas ahead of it. Produced by a combination of these effects, this large amplitude neutral gas pulse then dominates as the important component of impulse for at least 100 μsec. That is, the thrust during this period is mostly due to a transient impulse rather than the steady "blowing" provided by steady-state thrusters. This occurs even though nonchanging, or slowly-changing, terminal characteristics, light signals, or probe signals might have suggested the experiment was in a partly steady or quasi-steady realm. Thus, if a megawatt level pulsed MPD-Arc thruster is to simulate a steady MPD-Arc thruster, then it will have to be operated for longer pulse durations.

Peak total pressure profiles are presented in Fig. 3. These are shown for three different axial positions down the duct, Z = 25 cm, 30 cm, and 35 cm, and for two different peak arc current cases, 11.2 ka and 20.0 ka. Magnetic field is the parameter. The inversion of the profile shape with increasing field appears related to the effect of the magnetic field forcing ions (and ahead of the ions, neutrals swept up through collisions) to follow the expanding field lines rather than focusing them on centerline. This effect is more pronounced as the magnetic field is increased from 1.0 to 2.0 T at the 20.0 ka condition.

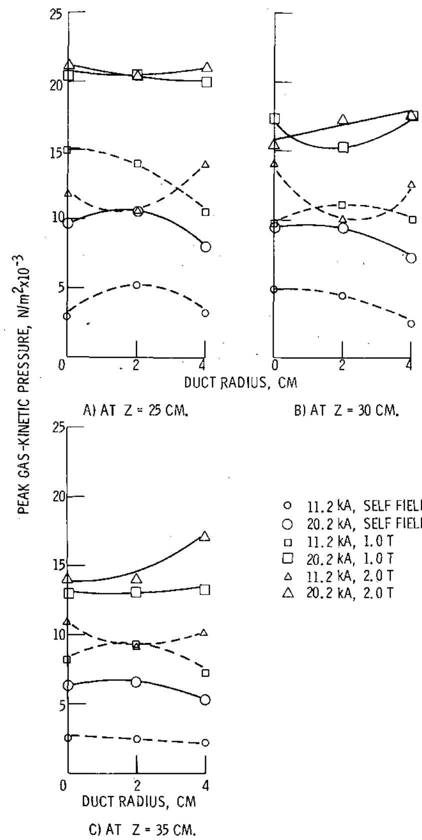

Fig. 3 Peak gas-kinetic pressure profiles.

The transit time for the total pressure pulse to pass by stations at Z = 35 cm is used to calculate the pulse velocity. Pulse velocities are in the range from 5000 to 20,000 m/sec. Calculation of the heavy particle number density was carried out assuming Newtonian flow for the Z = 30 cm position using the peak total pressure and the pulse velocity. The neutral number densities are about an order of magnitude larger than the plasma number densities (3) measured in the subsequent plasma portion of the flow.

To examine the question of propellant sweeping, an estimate was made of the amount of mass in the pressure pulse for one particular case, 20.0 ka peak arc current, and 1.0 T magnetic field. It was found to be about 10% of the mass of the propellant having left the thruster by that time.

References

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[3] Michels, C. J. and Sigman, D. R., "Exhaust Characteristics of a Megawatt Nitrogen MPD-ARC Thruster," *AIAA Journal*, Vol. 9, No. 6, June 1971, pp. 1144–1147.