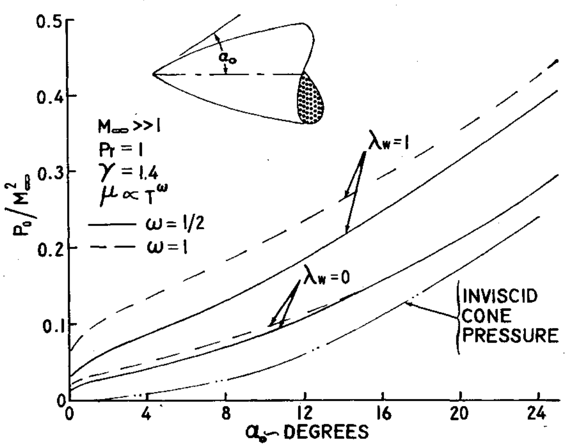

Fig. 1 Tip pressure ratio.

$\exp\{\zeta_0 C(1)/\beta\}$, which is Eq. (14) differentiated and evaluated at $F_0' = 1$, and $[1 + \zeta_0 P_0(1)]N_0(1)F_0''(1) = F_0''(0)$, which is the first expression in Eq. (11) integrated and evaluated at $Y = 1$. Equation (13) thus yields ζ_0 implicitly.

The principal result is the surface pressure. It is obtained from Eqs. (4) and (10) in the form $p_w/p_\infty = p_0 + 0(x)$ where, from Eqs. (4) and (12), $p_0 = (\gamma - 1)M_\infty^2\varphi^2/[2\zeta_0 F_0(1)]$. Some results for p_0 are shown in Fig. 1. A more complete presentation of results can be found in Ref. 4, which also includes some results for two-dimensional pointed-nosed bodies.

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Switch-Triggered Pulsed Plasma Accelerator Thrust Measurements

William J. Guman*

Republic Aviation Corporation, Farmingdale, N. Y.

THE electrical discharge in many pulsed plasma accelerators intended for space propulsion is initiated by injecting gaseous propellant into the interelectrode spacing of electrically charged electrode nozzles. Initiating an electrical discharge in this manner is frequently called "propellant-triggering." The advantage of this triggering technique is absence of a repetitive, fast-acting, high-current switch in the electrical network of the accelerator. However, propellant-triggered accelerators generally electromagnetically accelerate only a portion of the injected propellant. By introducing a switch into the electrical network it becomes possible to delay application of voltage relative to propellant injection and therefore to vary propellant utilization. This note presents experimental data showing that, with a switch-triggered pulsed plasma accelerator, it is possible to vary specific thrust even after the initial drop in thrust.[1]

During the propellant injection phase of a propellant-triggered accelerator, gaseous propellant expands across a valve seat and through injection ports into the evacuated interelectrode spacing of the electrode nozzle. The interelectrode gas pressure rises in the neighborhood of the injection ports, and an electrical discharge occurs during this pressure rise. Since the time-varying interelectrode pressure rises from a value below the pressure level corresponding to the low-pressure branch of a Paschen curve, the electrical discharge takes place with the breakdown voltage-pressure relationship represented by the equivalent of the low-pressure branch of a Paschen curve. Once the discharge is initiated, the mass distributed in the interelectrode spacing is swept out of the nozzle within a few microseconds. Because it is not possible to terminate propellant flow instantly, gaseous propellant usually continues to enter the interelectrode spacing after termination of the electrical discharge. It is neither possible to energize this "afterflow" of propellant, nor to inject, prior to the electrical discharge, an arbitrary quantity of mass having peak pressures near the high-pressure branch of the Paschen curve. An accelerator that uses a switch to delay application of voltage relative to propellant injection usually energizes some propellant "afterflow," besides making it possible for an arbitrary quantity of propellant, having an arbitrary peak interelectrode pressure, to be injected prior to the acceleration process. It must be noted, however, that switch-triggering offers no advantage over propellant-triggering if the maximum value of the injected time-varying interelectrode pressure is just equal to the minimum pressure required to initiate the electrical discharge by propellant-triggering (i.e., by shorting the switch). To utilize the advantages of switch-triggering, it is necessary to inject either more gaseous propellant, or gaseous propellant at a higher pressure, into a switch-triggered accelerator rather than into the same accelerator operated by propellant-triggering.

In the present study, a low-pressure, linear pinch-type switch was devised and inserted in series into the electrical circuit of a pinch-type pulsed plasma accelerator. The interelectrode spacing of the switch was left open to ambient background pressure of the vacuum chamber (10^{-4} to 5×10^{-4} torr), and the switch was "closed" by discharging four uniformly distributed Bendix surface igniter plugs into the interelectrode spacing of the switch. To preclude a potential across the electrode nozzle prior to switch activation, a large resistance was permanently connected across the two electrodes of the nozzle. Capacitor voltages ranging between 1 and 1.5 kv were examined during all of the studies reported herein, with discharge energies ranging roughly from 250 to 350 joules. Current traces of the main discharge were taken during accelerator operation with the switch shorted by a concentric shorting ring and were found to be essentially the same as when the switch was not shorted. A distortion of the current waveform, such as frequently encountered in low-pressure switches, was not observed. An electromagnetically driven valve† was used to inject gaseous propellant into the interelectrode spacing of the electrode nozzle. Only nitrogen was used as the propellant during the tests reported in the first part of this study. The upstream propellant supply pressure and the valve voltage were kept fixed at such values as to produce an electrical discharge for all imposed delays between propellant injection and voltage application. The accelerator assembly was mounted on a thrust stand, and thrust data was taken after the initial drop in thrust[1] as a function of the imposed time delay between valve activation (i.e., propellant injection) and engine voltage application.

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* Staff Engineer, Power Conversion Division. Member AIAA.

† Microvalve Model No. MV-12 AF, Space Sciences, Inc., Natick, Mass.

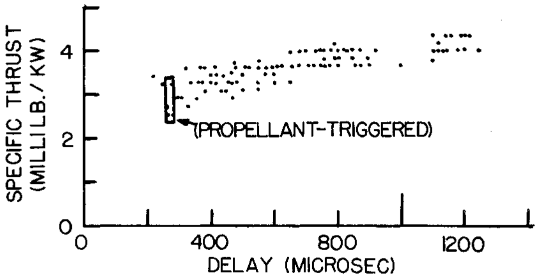

Fig. 1 Specific thrust as a function of imposed delay.

The current to the electromagnetically driven valve, the current to the igniter plugs of the switch, the voltage across the electrode nozzle, and the current of each discharge were displayed simultaneously on two Tektronix 555 Oscilloscopes. By shorting the switch with a cylindrical shorting bar, it was also possible to operate the accelerator by propellant-triggering.

Thrust data of several tests are presented in Fig. 1. It can be seen that the shortest time lag between propellant injection and electrical breakdown and the lowest specific thrust (based upon stored capacitor energy) were measured during propellant-triggered operation of the accelerator! Increasing this time lag by switch-triggering was found to increase the thrust nearly linearly with the imposed delay. The specific thrust of the accelerator could be raised by as much as 30% by imposing delays as long as 1500 μsec beyond the time when a discharge would have occurred had the discharge been initiated by propellant-triggering. The specific thrust could be varied even after the initial drop in thrust.[1]

The shortest time interval between propellant injection and electrical breakdown was found to be a function of voltage (i.e., energy) applied to the electromagnetically driven valve and propellant-supply pressure upstream of the valve. Figure 2 presents some data of this minimum delay time with the forementioned electromagnetically driven valve during propellant-triggered operation of the accelerator. At fixed values of valve voltage and propellant supply pressure, the interval of time between propellant injection and electrical breakdown was reproducible within a few microseconds. Statistically varying delays of the duration observed in Ref. 2 were not encountered in either propellant-triggered operation or in switch-triggered operation whenever gas was injected into the accelerator. It should be noted, however, that the observations reported in Ref. 2 were obtained in a stationary gas whose pressure exceeded the initial interelectrode pressure used during the present tests by several orders of magnitude and where discharge currents were roughly two orders of magnitude smaller than those encountered in the present study. From the results presented in Fig. 1, it can be seen that random delays, varying by as much as 100 μsec in the interval between propellant injection and electrical breakdown, would not appreciably affect the thrust level over the range of delays tested.

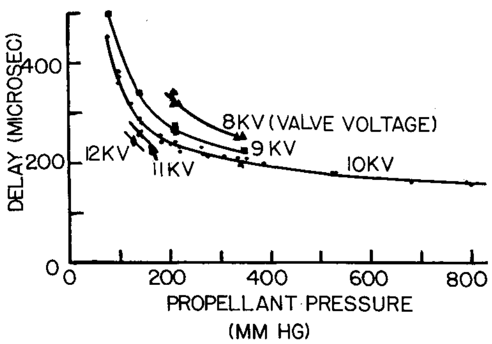

Fig. 2 Minimum delay as a function of propellant pressure and valve voltage.

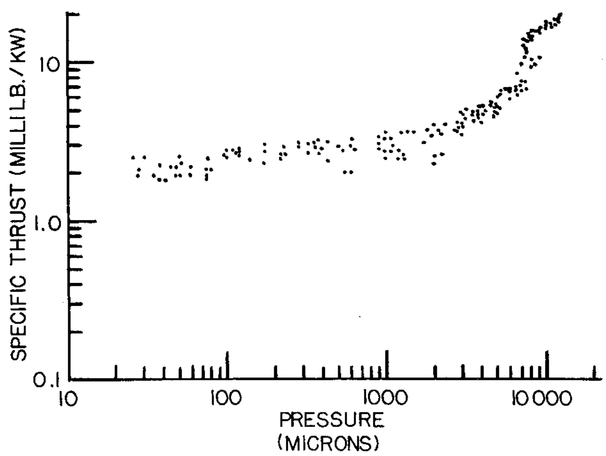

Fig. 3 Specific thrust as a function of interelectrode pressure.

No attempt was made during these tests to optimize specific impulse or efficiency. An optimization of these parameters is achieved by injecting the least quantity of mass compatible with just sustaining an electrical discharge for each delay that is imposed between propellant injection and voltage application.

The preceding results do not distinguish whether the observed increment in thrust was due to the additional mass that could be injected prior to the discharge, or due to an increased efficiency[3] in accelerating the particular interelectrode mass density distribution present at the time of discharge.

Thrust measurements were also carried out with the switched pulsed plasma accelerator discharging into a uniformly distributed stationary gas located in the interelectrode spacing. The entire switch-triggered accelerator was encased in a container and mounted on a thrust stand. This container was evacuated by a separate vacuum system from the one used to evacuate the vacuum test chamber in which the thrust stand was located. The interelectrode spacing of the accelerator electrodes was left exposed to the ambient background pressure of the vacuum test chamber. For convenience in testing, air was admitted to the vacuum test chamber and used as the propellant. Thrust data of the accelerator were taken with interelectrode pressure levels encompassing the entire pressure range of the Paschen curve. The uniformly distributed mass present in the interelectrode spacing was changed by almost three orders of magnitude, and, as can be seen from Fig. 3, the specific thrust (based upon stored capacitor energy), was negligibly affected by this large change in interelectrode mass, except near the high-pressure branch of the Paschen curve where, rather rapidly, the specific thrust increased by one order of magnitude! The measured peak specific thrust levels of nearly 20 mlb/kw are apparently the largest ever reported for pulsed plasma accelerators. Optimum specific impulse and efficiency occurs during these latter tests when the interelectrode pressure is at the low-pressure branch of the Paschen curve.

Additional studies are being carried out for the purpose of providing an understanding of the observed thrust behavior.

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