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A Low-Power MPD Thruster of Duoplasmatron Type

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IN the past decade many studies have been made of low-thrust thrusters for such missions as satellite station-keeping or attitude control. Recently some promising experimental results were reported for low-thrust plasma thrusters (steady or pulsed), which are physically and electrically simpler than electrostatic thrusters (ion or colloid) and reliable in operation.[1,2]

The Duoplasmatron, an arc-type plasma source due to M. von Ardenne,[3] has been used as an ion source for electrostatic thrusters.[4,5] This plasma source, with a baffle (Zwischenelektrod) and a magnetic coil, can be operated at high-ionization efficiency (low neutral emission) with a variety of propellants, by means of the effect of mechanical or thermal constriction and magnetic constraint. This Note is concerned with the development of a simple low-thrust plasma thruster, composed of a Duoplasmatron-type plasma source and a magnetic nozzle. In the present device, the magnetic nozzle is produced by the same magnetic coil used in the plasma source (Fig. 1). The results of the experiment with hydrogen propellant show moderate thrust efficiencies in the range of relatively high specific impulse. Although the background pressure is not sufficiently low to obtain accurate data of the performance of the thruster, these experimental results demonstrate its capability as a low-thrust plasma thruster.

Apparatus and Experimental Procedure

The performance of the thruster depends sensitively upon the shape of the baffle (mild steel) and the anode (copper).

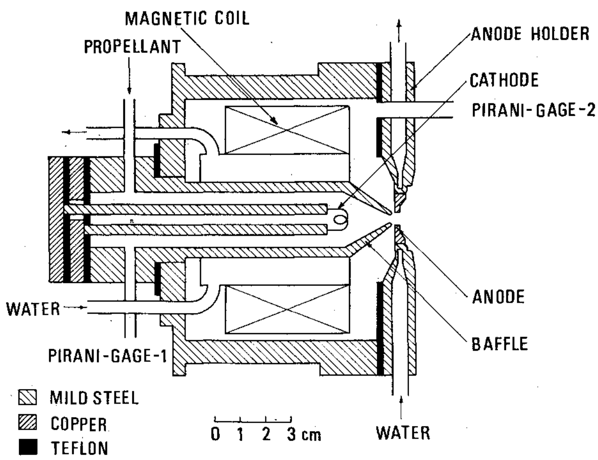

Fig. 1 Schematic of MPD thruster of Duoplasmatron-type.

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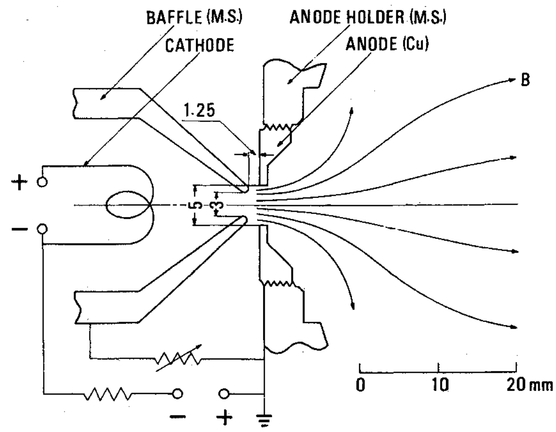

Fig. 2 Detail of electrode arrangement and magnetic field map.

The arrangement shown in Fig. 2 was finally adopted in the present experiment. This arrangement of the baffle and the anode holder (mild steel) permits shaping of the magnetic field (magnetic nozzle) such that it diverges in the exhaust region, when electric current flows through the magnetic coil. The magnetic field map in the figure was obtained by using iron filings. The average density of magnetic flux is of the order of 3000 gauss (coil current: 2.5 amp) at the throat of the magnetic nozzle.

In the present device with the thermionic cathode, the arc discharge can be initiated without any auxiliary equipment.[5] In the steady operation of the thruster, the baffle is maintained slightly positive of floating potential. The arc discharge produced is constricted by the baffle canal with throat of 3 mm diam (mechanical or thermal constriction), and the axial magnetic field between the baffle-tip and the anode further constrains the discharge (magnetic constraint). The combined effect causes formation of a cloud of hot dense plasma, which is expelled through the anode orifice of 5 mm diam and expands in the magnetic nozzle. The thruster has been operated mainly with hydrogen propellant, although some preliminary operations with argon propellant were also made. The gas pressure measured by Pirani gage 1 and 2 (Fig. 1) are of the order of 0.5 and 0.1 torr, respectively, for ordinary operating conditions.

The experiment was conducted in a 25-cm-diam by 40-cm-long bell jar, and the background pressure was maintained at about 2.5×10^{-3} torr (H_2 flow rate: 0.028 mg/sec) or 3×10^{-2} torr (H_2 flow rate: 0.033 mg/sec). It is reported that the background gas interferes with the normal thrust-producing mechanism, reducing the exhaust velocity, and also that it is entrained and accelerated by the thruster.[6] The experimental results shown in Ref. 6 suggest that the background pressure in the present experiment is not sufficiently low to obtain accurate data of performance. However, the present experiment will be useful to provide answers to the feasibility question of a plasma thruster of this type.

The thrust was measured by a pendulum-type thrust target.[7] A cone shape was chosen for the target, which would reduce any error caused by sputtered and rebounding particles. The target (cone diameter: 50 mm, length: 95 mm) was constructed of 0.2-mm-thick tungsten and was radiation cooled. A magnetic damper was attached to the bottom of the target and its deflection was determined optically with a cathetometer. In the present apparatus, the anode orifice diameter was sufficiently smaller than the cone diameter of the target, but the thruster diameter (anode holder diameter) was larger than it. So if the target is set too close to the thruster, the deflection of the target caused by rebounding particles between the thruster and the target becomes noticeable. If the target is set far from the thruster, it can not capture the spreading plasma beam completely. In order to

Table 1 Typical operating parameters of MPD thruster of Duoplasmatron-type with hydrogen propellant

Propellant flow rate, mg/sec	Magnetic coil current, amp	Discharge current, amp	Discharge voltage, v	Discharge power (P_D), w	Thrust (T), mN	T/P_D, mN/kw	Thrust efficiency, %	Specific impulse, sec
0.028	2.5	5	110	550	2.02	3.7	13.2	7360
0.028	2.5	4	145	580	1.82	3.1	10.2	6630
0.028	2.5	3	235	705	1.46	2.1	5.4	5320
0.028	2.5	2	180	360	0.99	2.8	4.9	3610
0.028	2.5	1	175	175	0.53	3.0	2.9	1930
0.028	1.5	5	110	550	1.32	2.4	5.7	4810
0.028	1.5	4	110	440	1.19	2.7	5.7	4340
0.028	1.5	3	100	300	0.39	3.1	5.2	3390
0.028	1.5	2	90	180	0.66	3.7	4.3	2410
0.028	1.5	1	85	85	0.42	4.9	3.7	1530
0.033	5	5	97	485	2.45	5.1	18.8	7580
0.033	5	4	90	360	1.80	5.0	13.6	5570
0.033	5	3	80	240	1.32	5.5	11.0	4080
0.033	5	2	74	148	1.00	6.8	10.2	3090
0.033	5	1	67	67	0.53	7.9	6.4	1640
0.033	2.5	5	75	375	1.13	3.0	5.2	3490
0.033	2.5	4	71	284	0.93	3.3	4.6	2880
0.033	2.5	3	68	204	0.75	3.7	4.2	2320
0.033	2.5	2	65	130	0.60	4.6	4.2	1860
0.033	2.5	1	60	60	0.40	6.7	4.1	1240

measure the thrust without any marked errors caused by these effects, an adequate distance between the thruster and the target was determined experimentally. The measured thrust T is used to calculate I_{sp} and η_T :

$$I_{sp} = T/\dot{m}g \qquad \eta_T = T^2/2\dot{m}P_D$$

The thrust efficiency η_T does not include the power of the magnetic coil and cathode heating.

Results and Discussion

Table 1 gives the experimental test results obtained with the present device using hydrogen propellant. It is noticed in the table that in the cases of relatively high specific impulse, thrust efficiency is fairly good, although the level of T/P_D is generally low. We suppose the values of thrust efficiency and specific impulse in the table are probably high by some unknown amount due to entrained and accelerated background gas, although this effect will not be large. The Duoplasmatron-type plasma source can be operated successfully with a variety of gases, and the use of a propellant with larger molecular weight may improve the figures of thrust efficiency in the range of low specific impulse and those of T/P_D, generally. Further experiments with other propellants are needed.

The performance of the present device is very sensitive to the magnetic field strength (magnetic coil current). In general, the increase of the magnetic field strength improves the performance, although accompanied with some increase of the discharge voltage (for a constant discharge current). The excessive increase of magnetic field above a critical value, which depends on the propellant flow rate and the discharge current, however, causes a marked increase in the discharge voltage and hence the degradation of performance. It is seen in the table, for the case of propellant flow rate of 0.028 mg/sec, that the magnetic field associated with a coil current of 2.5 amp is appropriate for discharge currents of 4 and 5 amp, but it is too strong for discharge currents below 3 amp. It is also seen that the increase of the discharge current (for a constant magnetic coil current) raises the thrust efficiency generally, but increasing it beyond the range covered in this experiment requires more efficient cooling of the baffle tip since an excessive temperature rise diminishes its magnetic permeability.

On the present device, in which a diverging magnetic field (magnetic nozzle) is applied to the discharge and exhaust region, there are several thrust mechanisms simultaneously present. We suppose in the present case of small discharge currents the "magnetic expansion process," which was found to be a main thrust producing mechanism in a low-power MPD thruster,[8,9] must be playing an important part.

The plasma density in the Duoplasmatron-type plasma source is rather high, so sputtering erosion of electrodes (including baffle) will be substantial. We are planning to substitute a hollow cathode of low work-function material for the filament cathode, but the erosion of electrodes may become a serious problem in the practical application of a thruster of this type. For near Earth low-thrust missions, the thruster weight is relatively important in total propulsion system performance.[10] The weight of the present device will be decreased considerably by the improvement of the magnetic-field producing system.

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