Comparative analysis of micro-cathode arc thruster performance

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Abstract: Propulsion systems based on electrically activated small thrusters that utilize chemically-inert solid propellants are beneficial for micro-satellite applications. Micro-thrusters are able to deliver small impulse bits and characterized by simplicity, scalability, low cost, low weight and high reliability. This paper analyzes performance of micro-cathode thruster in comparison with other commercially available thruster technologies operating at the same power range.

Nomenclature

Er	=	erosion rate
B	=	magnetic field
Isp	=	specific impulse

I. Introduction

Low-mass, low-volume propulsion subsystem for small satellites that would provide attitude control and station keeping duties is one of the key area of interest for US Army. Propulsion systems based on electrically activated small thrusters that utilize chemically-inert solid propellants are beneficial for these applications. Micro-thrusters are able to deliver small impulse bits of about several μN·s to satellites and characterized by simplicity, scalability, low cost, low weight and high reliability. In this work measurements of the key parameters of micro-cathode arc thruster

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(μCAT) are presented, and μCAT performance compared with other commercially available thruster technologies operating at the same power range.

II. Experimental set up and diagnostics

A. Experimental facility

μCAT testing was conducted in cylindrical vacuum chamber (about 450 mm length and 350 mm diameter) shown in Fig. 1. The chamber is equipped with vacuum ports for discharge electrodes, diagnostic probes, pumping, pressure gauges etc. The chamber is pumped by the diffusion (Varian VHS-6, pumping speed 2400 liters/s) and rotary (Alcatel 2033, pumping speed 585 liters/min) pumps. The residual gas pressure in the range of 5×10^{-6} -10^{-5} Torr is reached in the chamber.

Fig. 1. Experimental micro-propulsion facility

Variety of electrostatic Langmuir probe configurations and designs was utilized in order to monitor temporal evolution and spatial distribution of the parameters in exhaust plasma jet and inside the thruster channel. This includes measurements of plasma electron temperature, plasma density, plasma potential, ion velocity, erosion rate, thrust and ion current.[1,2,3,4]

B. μCAT operation principal

Schematic drawing of μCAT is presented in Fig. 2. μCAT uses an annular titanium cathode and copper anode having inner diameter of 4.85 mm and outside diameter of 6.35 mm. Length of new cathode prior the thruster operation is few centimeters (cathode is used as propellant and consumed at μCAT operation), while anode length is 1 mm. Anode and cathode tubes are positioned along same axis and separated about 1 mm between each other using ceramic insulator ring (see Fig. 2).

μCAT can be powered directly from the spacecraft bus without utilization of additional voltage converters. Parallel capacitor (typically hundreds of μF) is used to provide storage of electrical energy between the thruster pulses and fast release of the energy on the stage of the thruster pulse. μCAT is capable to operate on DC voltages as low as 10-30 Volts.

Obviously, discharge cannot be generated at application of several tens of Volts between the discharge electrodes. To this end inductor (hundreds of μH) included in series with the discharge electrodes is utilized. Magnetic energy stored in the inductor is released in the form of high-voltage pulse of about several hundred Volts and characteristic rise time of hundreds of ns. In order to ease the electrode breakdown, ceramic insulation ring is covered with conductive layer that is tuned to be in balance between its ablation on the stage of breakdown and re-deposition on the stage of thruster pulse. After the breakdown, energy is consumed from the inductor in the form of high current (in the range of 10-100 A) pulse with duration of several hundred μs.

Discharge between the electrodes is operating in the form of cathodic vacuum arc that is supported by erosion of cathode material at high pressure from micron-size cathode spots.[5] Utilization of magnetic field in μCAT ensures that cathode spots are attached to the interface between cathode and insulator, and rotates along the interface in retrograde direction guided by magnetic field. More details on μCAT operation principle can be found elsewhere.[1,2,3,4]

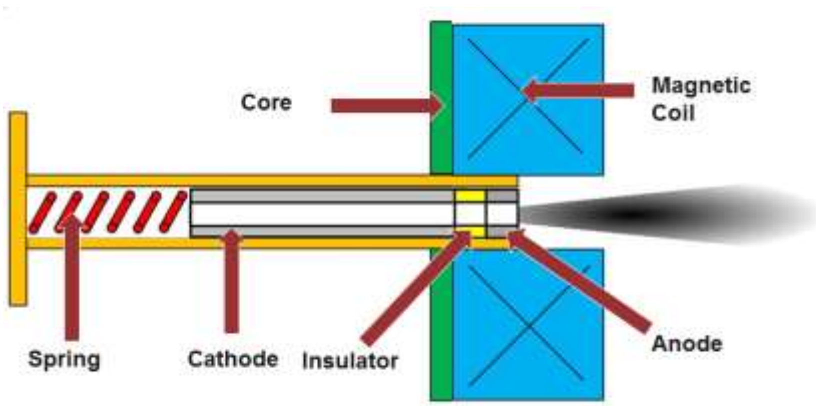

Fig. 2.μCAT schematics

III. Results and Discussions

Magnetic field plays important role in μCAT operation. The effect of magnetic field on plasma guiding along the thruster channel was studied.[1,3] It was shown that cathode erosion rate increases with application of magnetic field reaching saturated value of erosion rate of about *Er*=50 μg/C at *B*=0.3 T for Titianium cathode. The overall exhaust jet current was shown to increase by a factor of 50 with application of 0.25-0.3 T magnetic field in comparison with that without the magnetic field. This experimental data indicates that appropriate geometry and strength of magnetic field allows effective guiding jet along the thruster channel and minimizes plasma losses on the thruster walls.

Magnetic field influences uniformity of cathode propellant consumption.[1,3,4] It was demonstrated that at application of magnetic field cathode spot rotates along the cathode-insulator interface. This leads to corresponding rotation of the entire plasma jet along with the cathode spot from which the jet is originated. This was confirmed by measurements of temporal evolution and spatial distributions of currents in vicinity of cathode surface and outside the thruster in the exhaust plasma jet, as well as by visual observation of

Parameter	**Value**
Total mass of subsystem	300 g
Isp	2,000-3,500 s
Thrust	100 μN
Impulse bit	1 μN·s
Repetition rate	100 Hz
Power consumption	10 W
Exhaust velocity	20-35 km/s
Total propellant mass	40 g
Delta-V (for 4 kg satellite)	300 m/s
Peak current	50-100 A
Supply voltage from spacecraft bus	~20 Volts

Table 1. Parameters of mCAT propulsion system

cathode surface post-experimentally. Uniform consumption of cathode propellant at the edge with insulator ensures a propellant feeding by means of the spring (see Fig. 2) and provides long operation lifetime of the μCAT system.

Magnetic field also leads to acceleration of exhaust jet ions.[2] Ion velocity was measured to be around 2×10^4 m/s without a magnetic field. Application of magnetic field of up to 0.3 T does not affect ion velocity in vicinity of the thruster. However, ions are accelerated to about 3.5×10^4 m/s at distances of about 20 cm from the thruster head if magnetic field of 0.3 T is utilized.

The μCAT thrust measurements were conducted using a torsional thrust stand mass balance. Application of magnetic field led to increase of impulse bit from about 0.1 μN-s at B=0 to about 1.1 μN-s in the case of B=0.3 T. Back flux and contamination were studied using witness plates and single Langmuir probes.[6] It was found that virtually no backflux is detected since the plasma jet is nearly 100% ionized (due to utilization of cathodic vacuum arc).

Some propulsion-related parameters of μCAT system are presented in Table 1. The comparison of propulsion technologies operating in the low power range of <10 W is presented in Table 2. μCAT is one of limited number of technologies utilizing solid metal propellant. This benefits propellant carrying capability of μCAT system and leads to superior size/mass characteristics of the system compared to other technologies. μCAT is leader in respect of I_{sp} parameter (*Isp*=3500s), due to natural property of cathodic arc to produce extremely high-speed ions.[5] Both of these factors (large amount of carried propellant and high I_{sp}) ensures leadership of μCAT technology in Delta-V parameter. μCAT utilizes low operating voltage that can be easily supplied by the spacecraft without need in additional voltage conversion. Another important advantage of μCAT technology is absence of backflux,[6] due to high ionization degree of plasma jet and, therefore, motion of entire jet as a whole with high velocity.[5] Finally, μCAT technology is characterized by very high overall efficiency and thrust- to-mass ratio in comparison with competing technologies.

Parameter	**μCAT (GWU)**	**PPT (Clyde Space)[7,8]**	**PPT (Busek Co)[9,10,11]**	**Electrospray (MIT)[12,13,14]**	**Electrospray (Busek Co)[9,10]**	**VAT (Alameda)[15]**
Propellant	Metal	Teflon	Teflon	Liquid	Liquid	Metal
System mass, g	200	160	550	45	1150	600
System volume, cm^3	200	200	500	300	500	200
Voltage	Low	High	High	High	High	Low
Isp, s	3000	590	700	3000	800	1500
Propellant mass, g	40	10	36	20	75	40
Delta-V (for 4 kg satellite), m/s	300	15	63	150	151	151
Efficiency, %	15	4.7	16	71	31	9.4
Thrust to mass ratio, uN/g	0.63	0.03	0.18	0.5	0.65	0.22
Ionization degree	High	Low	Low	High	High	High
Cost	Low	Low	Low	High	High	Low
TRL	4	6	5	2-3	5	4

Table 2. Comparison of propulsion technologies operating in the low power range of <10 W

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