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CubeSat Propulsion Using Electrospray Thrusters

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ABSTRACT

The space industry is showing increasing interest in small, low-cost CubeSats which can serve a variety of missions. Busek Co, Inc is developing a small TOAC (thruster-on-a-card) that is designed to provide both primary and ACS propulsion within a 1U CubeSat volume. Electrospray thrusters operate by electrostatically accelerating charged droplets of an electrically conductive ionic liquid, and are capable of providing a high degree of throttling and variable Isp. The electrospray thruster, propellant reservoir and power processing unit and digital control interface unit (DCIU) occupy less than 1U and will provide over 350m/s delta-v for a 1kg CubeSat. The propulsion system presented here has a target thrust of 75μN, is designed to operate on a specific impulse of 800-1600s and a nominal power consumption of 2.5W. This propulsion system can be used to enable formation flying, pointing and orbit maintenance applications for CubeSats. This device has grown from AFRL and NASA development heritage, including Busek's recent delivery of 8 flight electrospray thrusters to Space Technology 7 Disturbance Reduction System (ST7-DRS) technology demonstration mission, sponsored by NASA's New Millennium Program and managed by JPL, slated to fly in 2011. This paper describes the electrospray thruster system and its capability.

INTRODUCTION

In electrospray thrusters, a controlled mass flow of propellant is fed, via surface wetting or capillary tubes, to a zone subjected to a high voltage electric field. The propellant is at higher potential than a facing electrode, called the extractor. Because of this extracting potential, the propellant is atomized into charged droplets, which in turn form an electrospray beam, producing thrust. The potential of the beam can be further increased by means of an accelerator electrode. A schematic is illustrated in Figure 1. The thrust throttling capability in electrospray thrusters is significant: by varying the propellant flow rate and the beam voltage within reasonable values, it can deliver a thrust ratio of 20 or better.[1] Selection of appropriate propellant flow rate and beam voltage have the further benefit of influencing the size and charge of the emitted droplets, permitting control of Isp as well, with Isp and absolute thrust tending to be inversely correlated.

Electric propulsion, generally with significantly greater specific impulse than more conventional approaches such as chemical or cold gas, is a highly compelling propulsion source for satellites. Most electric propulsion, however, is suitable only for larger spacecraft since their performance scales down poorly at smaller sizes and lower thrust levels.

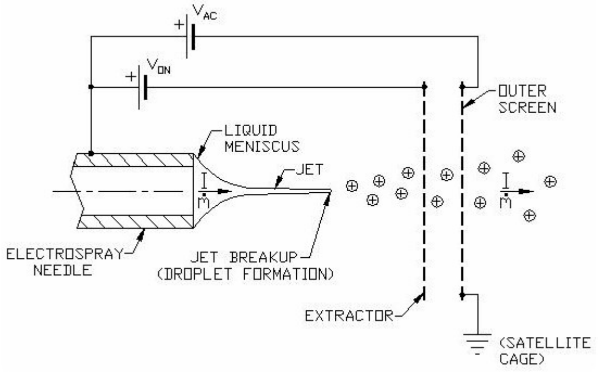

Figure 1: Schematic of electrospray thruster

Electrospray thrusters, alternately, are demonstrated to scale well to the size, mass, and thrust levels suitable for small spacecraft. Thruster performance does not experience the efficiency and life penalties typical of scaled-down versions of larger thrusters. A single electrospray emission site is some tens of microns in diameter, provides up to 5μN thrust, and consumes approximately 10mW. Single emission site thrust efficiencies are in the 80% range, and scale-up via multiplexing does not indicate any efficiency impact from emission site interactions. In reality, with primary system efficiency being driven by power supply conversion losses, scale-up to milliNewton thrust levels, comprised of some hundreds of emission sites, provides highly favorable improvements in overall system efficiency.

Busek Co. Inc. in May 2008, completed delivery of a pair of colloid thruster clusters for the NASA ST7 mission. These thrusters, selected for their unique capabilities in precision thrust control and low-noise operation, are the culmination of a six-year and nearly $20M development effort by Busek characterizing thrust performance, including lifetime, plume geometry, spacecraft contamination, spacecraft charge neutralization, power electronics design, thruster throttling, thermo-vacuum testing, vibration testing, shock testing, radiation exposure, and thruster controls. The basic technology is fully-vetted and has been NASA flight qualified.

The NASA ST7 thrusters were developed with a specialized application in mind: the most ultra-precise thrust for maintaining spacecraft position for large-scale interferometry applications. As such, these particular thrusters are not well-suited for many other missions.

The fundamental technology of electrospray thrusters, however, is highly attractive for the reasons mentioned previously, including the diversity of ionic liquid propellants, the improvements in miniaturization of electronics, and growing experience with electrospray system development. Because of this, electrospray thrusters can be constructed to service other missions as well.[2,3] Given the opportunity to fulfill propulsive niches and Busek's unique expertise in the ST7 development effort, Busek has been actively pursuing the development of electrospray thruster variants that span the operational regime from .01μN to 5mN.[4,5] Within this portfolio, Busek has also developed a relatively simple, rugged electrospray thruster variant suitable for use in Cubesats given their small size, low power requirements and simple design. This paper, after providing a brief discussion of the first flight tested colloid thruster, will provide a more detailed view of this simple thruster.

NASA ST7 THRUSTERS

The NASA Space Technology 7 (ST7) mission is a technology demonstration mission seeking to test femtoNewton force measurement sensors developed by the European Space Agency (ESA), and to use these force measurements to command microthrusters to maintain spacecraft position relative to an internal, freely-floating test mass.[6] Selected performance requirements for the microthrusters are:

Table 1: ST7 Performance Requirements

Parameter	Requirement
Thrust	*5-30 μN*
Thrust Resolution	*0.1 μN*
Thrust Noise	*0.1 μN /√Hz from 1 to 30 mHz*
Lifetime	*3300 Hrs*

A photograph of one of the flight units is shown in Figure 2. As previously mentioned, the ST7 mission requirements focused primarily upon ultraprecise performance, necessitating a large suite of power and control electronics, vital signs monitoring, and electrical isolation of multiple independent thrusters and propellant feedsystems.

Figure 2: NASA ST7 Cluster of 4 independently operated colloid thrusters with 90 days' propellant supply, 4 power processing units (PPU), field emission cathode, and digital control and interface unit (DCIU)

Demonstrated thrust throttling is shown in Figure 3. Thrusters are capable of multiple startup/shutdown cycles for bang-bang operation, or can operate continuously while modulating thrust over large throttling range. In the case of the NASA ST7 thrusters, thrust resolution can be adjusted to 0.01 μN precision and steadily maintained. Figure 4 provides an example of measured thrust noise while operating at intermediate thrust levels, indicating levels of ≈0.01 μN/√Hz between .001 and 2 Hz.

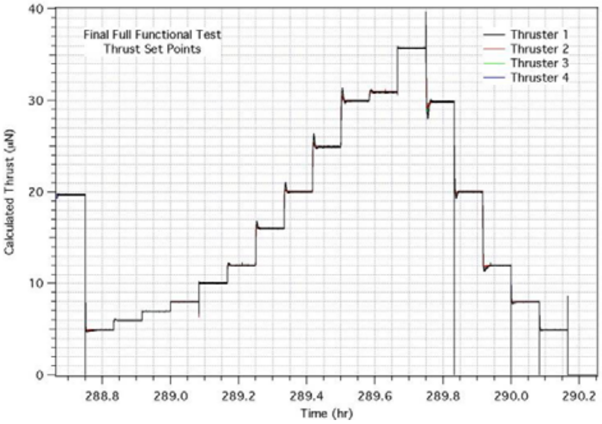

Figure 3: Illustration of dynamic range of thrusters, operating 5 to 38.5 µN (overlay of 4 thrusters operating simultaneously)[7]

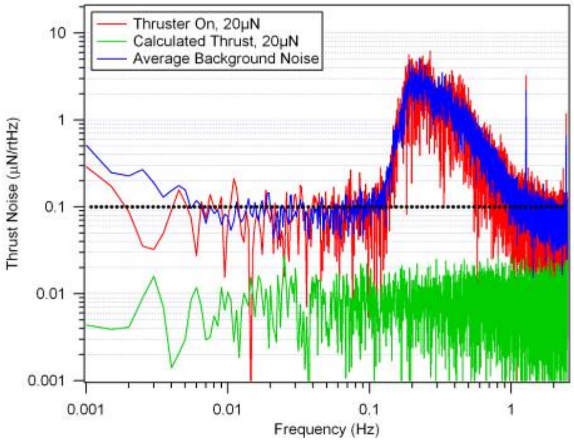

Figure 4: Measured thrust noise, using Busek-developed magnetically levitated thrust stand[7]

THRUSTER ON A CARD (TOAC)

The Busek TOAC is an extension of the single capillary electrospray emission site principle used in the NASA ST7 thrusters. This approach utilizes a planar, propellant-wetted surface as an initiation site for multiple electrosprays, providing much higher thrust in a small package (by a factor of 3-5), but with a penalty of variable droplet size affecting maximum attainable Isp as well as some loss of throttling fidelity (though compared to similar-class thrusters, still very favorable). By relaxing the NASA ST7 requirements and increasing the number of emission sites, this thruster design is capable of delivering 3 times the thrust in a fraction of the volume (10cm x 10cm x 5cm).

Target thruster lifetime is on the order of 1,000 hours, and it is expected that application of life-extending techniques from the NASA ST7 design will provide lifetime exceeding 5,000 hours.

The thruster head is shown in Figure 5. The emission region is 5mm diameter (referred to as TOAC-5 hereafter). Propellant reservoir, electrodes and high voltage isolation components increase the overall volume footprint to 3cm thick x 7.50cm diameter.

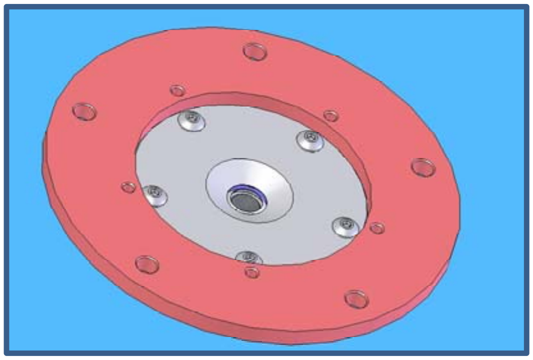

Figure 5: View of a planar emitter surface colloid thruster under development

Current development efforts are focused on emitter optimization, ejected plume characterization, and time of flight measurements. The time of flight measurements, accompanied with direct thrust measurements, provide validation of thrust and Isp.[2,8] This data is consistent with predicted values based on measured thruster voltage and current.

The thruster operates by the modulation of a single thruster parameter, emitter voltage. Above some “turn on” limit the voltage will draw propellant to the surface of the planar emitter and form a multiple-emission electrospray. Figure 6 shows thrust modulation of a TOAC with an emission region of 3mm diameter (TOAC-3) using only the extraction voltage to modulate the thrust output.

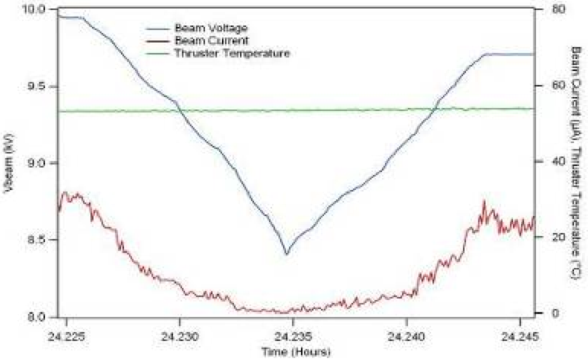

Figure 6: This graph demonstrates that the emission from the thruster can be modulated by beam voltage changes alone

Figure 7 depicts a typical test run achieved during testing of a TOAC-3.

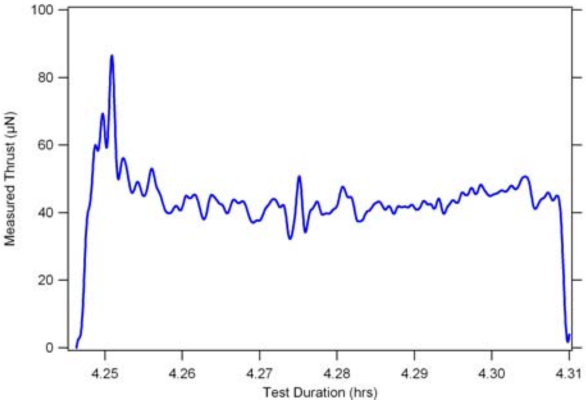

Figure 7: Direct thrust measurements made by Busek's magnetically levitating thrust stand[8]

Figure 7 demonstrates that a particular single planar emitter source is capable of delivering 50µN thrust from an emitter surface of less than 3mm diameter. The Isp and thrust will vary with operational setpoints, and parametric tests on the TOAC-5 indicate nominal operation of 50-75µN resulting in a specific impulse range from 800 to 1200 seconds. TOAC-5 thruster efficiency for this nominal operation is calculated to be approximately 80%.

NO MOVING PARTS

Busek eliminated the need for an active flow control (i.e. no valve) and pressurized propellant storage (i.e. no bellows) by introducing a self-regulating feed system. The advantages are: (a) the system has no moving parts, making it very reliable, (b) the removal of a valve and associated electronics yields a more compact thruster unit (with no sacrifice of thrust or Isp), (c) temperature control requires less power, and (d) the overall construction cost is reduced significantly.

The device, shown in Figure 8, relies on electrostatic forces and surface tension to supply propellant to the planar emitter at a regular rate.

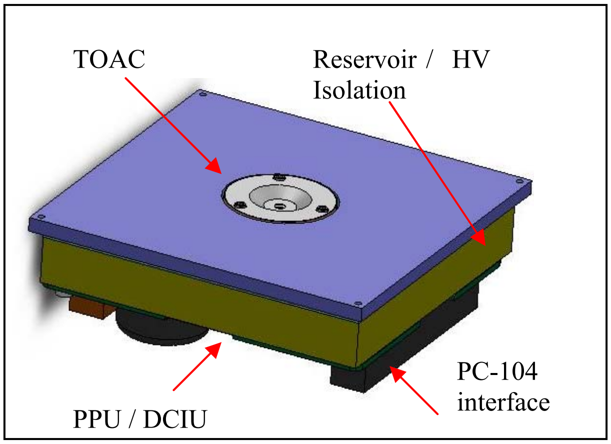

Figure 8: 3D CAD view of TOAC

The primary obstacle to a valveless thruster is propellant isolation during ground operations and launch. Isolation is important because the ionic liquid propellant's hydrophilic characteristics lead to absorption of water from environmental humidity. Adsorbed water in the propellant boils off when exposed to vacuum, interfering with proper thruster performance. Busek has demonstrated a simple, non-mechanical technique for isolating the bulk propellant from absorbing contaminants while on the ground. The isolation technology has been demonstrated via helium leak detectors to be leak proof to 10^{-10} Torr-L/sec. The technology is currently undergoing long duration testing (6 months).

INTEGRATED ELECTRONICS

Operation of the thruster requires a DC-DC Converter capable of delivering up to 10kV. Because the required current is low, this can be achieved in a footprint that is compatible with Cubesat requirements. To meet these needs Busek has developed a simple power processing unit (PPU) with integrated signal conditioning for thruster telemetry. This PPU establishes electrical isolation and control of the primary emitter/ thruster as well as the facing extractor electrode. Integrated within this package is also a digital control and interface unit (DCIU) that uses a digital interface to receive thrust commands and send back thruster telemetry to a primary motherboard. Power, telemetry and control all pass through a COTS connector (Figure 8) for integration into the host Cubesat. The DCIU / PPU can operate off a 3.3V, 5V or custom bus voltage.

ENABLING A NEW CLASS OF MISSIONS

The TOAC shown in Figure 8 features a propellant reservoir containing enough propellant for the thruster to operate for over 5,000 hours. This reservoir can be increased or decreased depending on mission requirements. In the course of flight hardware development and testing for ST7, Busek successfully operated a colloid thruster for over 3400 hours[9]. Post operation analysis revealed no degradation of the thruster, and it is expected that a 5,000 hour test with TOAC-5 will be as successful. This propulsion system enables a new class of Cubesat missions, increasing the relevance and versatility of Cubesats.

Formation Flying

After startup, the thruster output can modulate, imparting control over the flight path of the Cubesat. One of the most appealing features of Cubesats is their low cost for construction and insertion into orbit—a fleet of Cubesats outfitted with the TOAC-5 could be inserted by a primary launch vehicle (e.g. ESPA class) and self-distributed over a larger coverage area for science / observation missions.

Self-propelled Cubesats also could flexibly respond to mission modification. For example, failure of a particular Cubesat that is part of a larger network could be compensated for by repositioning of surviving Cubesats to fill in coverage gaps.

Plane Change

Assuming a Cubesat in an 800 km circular orbit, a plane change by angle θ takes a $\Delta v=v\cdot\theta$. Here, v is the orbital velocity, $7.3\cdot10^3$ m/s and Δv is the 350 m/s enabled by TOAC-5. This results in a total plane change of 0.048 radians, or about 2.7°. For optimal orbit plane change, the Cubesat wouldn't be expected to thrust constantly, but rather only when it is near the pivot points. There are two in each orbit, where it crosses the desired orbit. Assume the TOAC-5 thrusts 15% of the time, then the total time to make the maneuver is about $3.1\cdot10^7$ s, just under one year.

Orbit Maintenance

Cubesat observation missions using a CCD or other optical means are especially limited in space and volume: a rugged focusing lens can occupy a significant fraction of the internal Cubesat volume. Moving a Cubesat closer to earth would improve resolution. For example, a 1U Cubeat using a camera lens at an altitude of an 800km circular orbit can achieve an improved resolution if it operated at an altitude of 300km. The drag at 300km for a 10x10cm surface area Cubesat is approximately 11μN. If the Cubesat thrusters operated during 50% of the orbit, a TOAC-5 could maintain a 300km altitude for at least 300 days.

Deorbit

As the number of satellites in orbit increases, so does the collision hazard from satellites that are no longer functioning but are still in orbit. The need for such assets to be de-orbited has become apparent, as recognized by United Nations rules and DoD Instruction 3100.12 (Space Support) that requires satellites in low earth orbit to de-orbit in less than 25 years.

A thruster package enables the application of an intermittent force during only part of each orbit. The orbit can be changed to an ellipse with apogee at the original altitude but lower perigee, as sketched in Figure 9. The drag at the lower perigee will deorbit the asset.

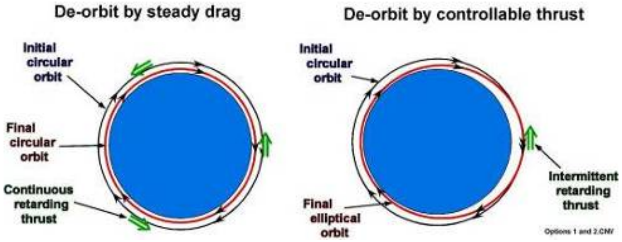

Figure 9: De-orbiting by thrust requires only half as much impulse as a steady deceleration

We see this as superior to passive methods that have been proposed such as balloons, sails, parachutes or tethers. These options are difficult to deploy and keep extended. A balloon, for example, is highly vulnerable to micrometeorites. The balloon would have to expand and then somehow become rigid. It would also be vulnerable to erosion by atomic oxygen bombardment. Near-earth gas is mostly oxygen. Bombardment by atomic oxygen would erode any low atomic weight materials by sputtering. To resist erosion, the sail or balloon would have to be made of a high atomic weight material, increasing its mass.

So far, all attempts to deploy multi-kilometer tethers have failed. To avoid being cut by a micrometeorite, multi-strand tethers are needed. To avoid rotating, the tether must be kilometers long with a weighted end, for gravity-gradient stabilization. Even then, it is subject to many modes of oscillation that must all be stabilized. If voltages developed between tether and plasma (e.g. because emission from the cathode was interrupted, even momentarily), the capacitance represented by the tether would charge up, then could discharge in an arc, damaging it. Oxygen bombardment, even if it didn't erode the tether, would deposit oxygen in the metal, gradually converting it to non-conducting oxide.

Tethers are also ineffective in polar or near polar orbits where many small satellites operate.

The TOAC-5 enables control of the descent of the satellite and is not subject to the same vulnerabilities as the passive methods previously described. A Cubesat operating at an 800km circular orbit, for example, can be brought to a 200km perigee (at which point atmospheric drag would overcome the asset in a matter of days). The velocity change is $\Delta v = 165$ m/s. (transfer to a 200 km circular orbit requires $\Delta v = 329$ m/s). If the asset mass is 1kg, the needed impulse is 165 kg-m/s. The total fuel expended would be 0.017kg (assuming 1000s specific impulse), which is well within the mass envelope of a 1U Cubesat.

ACKNOWLEDGMENTS

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