LOW POWER, HALL THRUSTER PROPULSION SYSTEM

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Abstract

In this paper Busek Co. Inc. presents the results of a U.S. Air Force Research Laboratory sponsored program to develop the key components of a low power, Hall thruster propulsion system including a nominally 200 Watt Tandem Hall thruster, 3.2-mm hollow cathode and a breadboard of discharge power DC-DC converter which is the critical part of the power processing unit (PPU). The thruster designated BH-T-200-X2B and the low power, low flow cathode designated BHC-1500-25 were delivered to AFRL for further testing. The thruster employs a unique, patent pending geometry, consisting of radially extended discharge chamber/plenum section and short acceleration zone at the thruster exit. The thruster uses a single, coaxial electromagnetic coil located upstream of the discharge chamber. The axially consecutive juxtaposition of the coil, the discharge chamber and the acceleration zone lead to its name - the Tandem Hall thruster.

At nominal conditions the thruster, powered by the breadboard delivers 11.4 mN of thrust at 1570 sec anode I_sp and 42% anode efficiency which excludes the cathode flow and the magnet power. The total (including all losses) I_sp and efficiency at nominal conditions are 38% and 1380 sec respectively. The 3.2-mm hollow cathode self-sustains, i.e. uses no keeper or heater power, at Xe flow rate approximately equal to 13% of the thrust flow. The converter breadboard operates form 28 VDC input and delivers real time continuously adjustable output voltage from 0 to 350 Volts or real time continuously adjustable discharge current from 0 to 1.25 Amps. The converter efficiency, which includes the control power taken off the 28 VDC input, exceeds 92%.

Introduction

Large segment of the military and commercial satellite market are evolving towards smaller size and lower cost while maintaining capabilities similar to the larger satellites built in the past. This trend is enabled by miniaturization of all electronic components and sensors commonly used on satellites. Rapid progress along this path is forced by reducing military budgets and by cost pressures on various satellite-based commercial projects. Small satellites cost less to produce, launch and operate. They can be produced quickly and launched on small vehicles saving millions of dollars.

The LightSats or micro-satellites are likely to be deployed in low earth orbits where they encounter significant atmospheric drag. Some may be deployed in constellations with precise relative positioning requirements. These and other applications place extraordinary demands on on-board satellite propulsion to maintain orbit, relative position, etc. Electric propulsion (EP) is well suited for these satellites because of high I_sp with corresponding reduction in propellant mass. In addition, decreasing satellite mass leads to an increase in its surface-to-volume ratio providing more surface for photovoltaics per unit satellite volume. This trend also favors low power EP. The U.S. Air Force has been a leader in EP development and sponsored research effort on various thrusters since the 1960’s. More recently, the Hall thruster initially proposed in both the United States and Russian and later perfected in Russia, was recognized by the Air Force as a very attractive ion accelerator due to its high performance and relative simplicity.

As a result, Busek was funded by the U.S. Air Force Research Laboratory to develop a small, 200 W Hall thruster under a multiphased SBIR program. This program is now completed, achieving and exceeding its objectives. All major subsystems and components of a nominally 200 W Hall thruster system including:

1. The thruster
2. Miniature cathode
3. Power processor unit (PPU)/discharge converter

were constructed and tested first individually and later as a system.

The propellant management system (PMS) was excluded from this program because of its technical maturity. Discussions with PMS suppliers, indicate that space qualified hardware of the appropriate size exists and can be delivered when needed. A PMS technical issue is the use of a special xenon flow controller that is employed by the Russian SPT’s which regulates the Xe flow in proportion to the discharge current. It is not clear that this complexity, which gives the thruster efficient throttling ability, is needed for the low power
thruster. While efficient throttling may be desirable for some missions, our present experience indicates that closed loop flow vs. discharge current control is not required for operational purposes.

A run-off between three thruster designs was performed and one was be selected for further development and optimization. Input power in the range of 100 to 300 Watts was explored. The selected thruster who's design and performance will be described in subsequent sections is shown in Fig. 1 along with its low power cathode.

Fig. 1 Busek’s 200 W Hall thruster (BHT-200-X2B) with associated hollow cathode (BHC-1300)

The development of the new cathode was necessitated by the lack of existing low power, low propellant consumption, physically small hollow cathodes. Those presently available are typically comparable in size to the 200 W thruster and consume a significant fraction of the propellant flow and the available power.

The low power Hall thruster power processing units (PPU) was developed concurrently with the thruster to avoid delays in deployment of the thruster and to exploit thruster/PPU integration design opportunities. To focus the limited resources, the PPU effort concentrated on the development of its critical portion, the discharge DC-DC converter and demonstration of its stability while powering the thruster. Other portions of the PPU such as an input filter, cathode heater, automatic event sequencing, etc. was de-emphasized because they are directly transferable from the larger, existing kW class units and pose no engineering difficulties. The as-tested breadboard rated at 400 W input power is shown in Fig. 2.

The subsequent sections will describe the thruster and the cathode design and performance. Description of the discharge converter will be summarized. A companion paper describes the converter and the dynamic behavior of the discharge in detail.

Fig. 2 Busek’s 400 W Hall thruster discharge converter breadboard

Design and Specifications of the BTHT-200 Thruster

A fundamental design requirement that applies to all Hall thrusters is that the electron and ion Larmour radia ($\rho_e$ and $\rho_i$, respectively) must satisfy the relation

$$\rho_e < \ell_s < \rho_i$$  \hspace{1cm} [1]

where $\ell_s$ is the characteristic dimension of the thruster over which the plasma interacts with the applied magnetic field $B$. Because $\rho$ is inversely proportional to $B$, it follows that

$$\ell_s \sim \frac{m_i c_i}{eB}$$  \hspace{1cm} [2]

where $m_i$ and $c_i$ are the propellant ion mass and velocity respectively. This relation dictates that small low power Hall thrusters must have large magnetic fields. Providing this field has proven to be very difficult when using the conventional magnetic circuit that utilizes magnetic coils inboard and outboard of an annular discharge cavity. For a thruster size smaller than few hundred Watts there is little space for the thermally demanding inboard coil, having been occupied by the inner magnetic pole that must be large enough to avoid saturation while conducting increasing $B$. One way to overcome this difficulty is to abandon to conventional magnetic circuit geometry in favor of a single coil structure located axially upstream (in tandem) of the discharge chamber as depicted in Fig. 3 which shows the typical cross-section of a patent pending tandem style thruster. This design approach allows the coil to grow to arbitrary diameter reducing its current density and simplifying its heat rejection and turn to turn insulation. The same approach permits the discharge chamber to grow radially beyond the outer diameter of the thruster annular exit creating a plasma plenum section. This in turn facilitates long residence time, uniform propellant distribution with homogenous plasma which is critical for both performance and life of the thruster.
The Tandem style discharge cavity therefore has two distinct zones with radially extended plenum section and very short acceleration section at the thruster exit. One of the key features of this cavity is that most of its surface is metallic and acts as propellant injector and a large surface area anode. Metal cavity surface reduces ion flux to the walls, yielding higher efficiency discharge. The metallic cavity walls also insure absence of substantial internal electric fields that could drive charged species into the walls increasing both losses and heating of the structure. Heat rejection from the cavity/anode is easily facilitated by the exposed external surface of the metal walls (unlike the SPT designs where the anode is surrounded by dielectric walls). Electrons are prevented from reaching the exterior side of the cavity by a grounding screen.

Steeply rising magnetic field flux in the exit area of the thruster where the intense discharge occurs is accomplished by making the cavity out of feromagnetic material to shunt away the undesirable portions of the B field upstream of the thruster exit. This shifts the peak magnetic field past the thruster exit plane. By virtue of its electrically and magnetically conductive walls, the cavity interior is free of E and B fields. Both features contribute to higher performance and primarily to longer life.

Propellant is injected into the cavity in its upstream outer corner, the location of an integral propellant manifold. The manifold is fed by two propellant lines through ceramic isolation devices located inside the electron screen. This permits grounding of the propellant tubes to the back flange of the thruster.

The exit portion of the thruster is covered by dielectric material. The inner pole is completely covered with a cone shaped dielectric cap. Experience has shown that this dielectric cover improves performance.

The six external ribs visible in Fig. 1 complete the magnetic flux return path and ensure structural integrity of the thruster.

The nominal size and performance specifications for the BTHT-200 thruster are shown in Table 1. At 207 Watts and 300 Volts and Xe mass flow of 0.74 mg/sec, the engine delivers 11.4 mN of thrust with anode $I_{an}$ of 1570 sec and anode efficiency of $\eta = 42\%$. The anode $I_{an}$ and $\eta$ exclude cathode flow and magnet power. The mid diameter of the exit annulus of the thruster is 21 mm. Its overall length is 12 cm and overall diameter 10.5-cm. Its current unoptimized weight is below 1 kg.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>BHT-200-X2B Specifications</th>
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<tr>
<td>Acceleration Annulus Mid-Diameter</td>
<td>21 mm</td>
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<tr>
<td>Input Power</td>
<td>207 Watts Nominal</td>
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<tr>
<td>100 - 300 Watts</td>
<td></td>
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<tr>
<td>Discharge Voltage</td>
<td>300 V Nominal</td>
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<tr>
<td>200 - 400 V</td>
<td></td>
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<tr>
<td>Propellant Mass Flow Rate</td>
<td>0.74 mg/sec (Xe) Nominal</td>
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<td>0.30 to 1.01 mg/sec (Xe)</td>
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<tr>
<td>Thrust</td>
<td>11.4 mN Nominal</td>
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<tr>
<td>4 to 17 mN</td>
<td></td>
</tr>
<tr>
<td>Anode Efficiency</td>
<td>42% Nominal</td>
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<tr>
<td>20 to 45%</td>
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<tr>
<td>Anode Specific Impulse</td>
<td>1570 sec nominal</td>
</tr>
<tr>
<td>1200 - 1600 sec</td>
<td></td>
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<tr>
<td>Thruster Mass</td>
<td>&lt;1 kg</td>
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<tr>
<td>Thruster Dimensions</td>
<td>10.5-cm diameter, 12-cm length</td>
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Design and Specifications of the Low Power, Low Flow Cathode

The 3.2-mm (1/8-in.) hollow cathode designated BHC-1500-025 is conceptually identical to the commercially available 6.3-mm (1/4-in.) hollow cathode with a design heritage in the Space Station plasma contactor. We focused on development on a low heat loss cathode to ensure self sustain operation at the nominal 200 W thruster discharge current of 0.7 Amp while minimizing the cathode flow rate.

Figure 4 shows a photograph of the BHC-1500-025 cathode along with its basic size and performance specifications. The major components are refractory metal tube with an orifice at its down stream end. The tube houses a tungsten emitter element impregnated with various oxides to achieve low work function. A swaged heater cable is wrapped around the tube and the tube/heater assembly is enclosed by tubular shell which contains the keeper on its downstream end. Flow is delivered through a ceramic isolator. In normal operation the cathode float and the propellant line upstream of the isolator is grounded.

From cold state the cathode can be started under three minutes. In a stand-by mode, when all the emitted electrons are collected by the keeper, the cathode operates with less than 0.05 mg/sec of xenon flow rate and a keeper voltage of about 20 Volts. Lower keeper voltage can be achieved by increasing the cathode orifice size which in turn leads to an undesirable increase in self sustained mass flow rate. When operating at nominal conditions of the thruster, the cathode mass flow rate is increased to 0.08 mg/sec (=13% of the thruster nominal flow), while delivering 700 mA. This allows the cathode to operate in a self
sustained mode - no keeper and no heater power. To date the cathode operated for about 250 hours without any deterioration in performance.

**Miniature Hollow Cathode Specifications**

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<table>
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<tbody>
<tr>
<td>Discharge Tube Diameter</td>
<td>3.2 mm</td>
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<tr>
<td>Emitter</td>
<td>Low Work Function Material</td>
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<tr>
<td>Ignition Time</td>
<td>&lt;3 minutes</td>
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<td>Stand-By Mode</td>
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<td>Keeper I, V</td>
<td>700 mA, 20 V</td>
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<td>Mass Flow</td>
<td>0.05 mg/sec, Xenon</td>
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<tr>
<td>Operating Mode</td>
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<tr>
<td>Heater I, V</td>
<td>Self-sustaining, No heater power</td>
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<tr>
<td>Mass Flow</td>
<td>0.04 mg/sec, Xenon</td>
</tr>
<tr>
<td>Discharge Current</td>
<td>700 mA</td>
</tr>
<tr>
<td>Cathode Mass</td>
<td>&lt;200 grams</td>
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</table>

*Fig. 4 Picture and specifications of the BHC-1500-025 self-sustaining hollow cathode*

**Design and Specifications of the Discharge DC-DC Converter**

Table 2 shows the major PPU/discharge converter specifications. The converter was designed to deliver up to 400 W to the thruster. To make it widely applicable, its output voltage and its output current is continuously variable from 0 to 350 V and from 0-1.25 V, adjusted in real time in response to an external analog signals. The user selects either voltage or current control or can preset maximum current while in voltage control. This capability, which may not be needed in most PPUs, automatically provided a 1.25 Amp current limit and short circuit protection. (Short circuit protection is a mandatory feature in all PPUs). The continuously adjustable current also facilitates easy control over many parallel connected systems at higher power PPU for larger thrusters be needed in the future.

The power topology selected for the converter consists of a buck derived pulse width modulated full Mosfet bridge followed by a dual bridge seriesed rectifier shown schematically in Fig. 5. Phase shift control is used for pulse width modulation of the Mosfet bridge in order to obtain resonant transitions for maximum efficiency. A switching frequency of 50 kHz was selected as a compromise between switching losses and size of the imagnetics. The PWM control circuit is based upon the Unitrode UC 1879 Phase Shift Controller IC. This IC is capable of operation at frequencies up to 300 kHz.

The primary bridge configuration is especially suited to high voltage and high power operation because it limits the voltage stresses on the Mosfets to the actual input line voltage. In addition to eliminating corona risk, this allows selection of lower resistance (R_{on}) Mosfets than would be possible with a push-pull or forward converter topology. Further advantage of the bridge is its compatibility with resonant transition phase shift modulation. The rectifier consists of ultrafast, high voltage diodes in a dual seriesed bridge to lower device stresses during reverse recovery.

*Fig. 5 Hall thruster discharge power supply/DC-DC converter schematic*

The planar winding power transformer uses a combination of printed wiring board and flat sheet metal (copper) windings. Planar construction offers important features such as low skin effect losses and parameter repeatability.

The breadboard was constructed on a flat aluminum baseplate that can serve as a heat path for conduction cooling inside a vacuum chamber and in an ambient room environment. It was designed to require no active cooling when operating in air. The baseplate dimensions are 11.5 x 9 x 3/8", as visible in Fig. 2. Without the base plate, but with all mounting hardware and connectors, the breadboard weighs 975 grams.

As shown in Fig. 6, the breadboard efficiency plotted as a function of output power (at several constant output voltages) exceeds 92% over the power range of interest from 150 to 350 Watts. Efficiency versus output current, shown in Fig. 7, exceeds 90% for all discharge currents over 0.5 Amps and voltages over 250 Volts. As mentioned previously, these efficicencies include control power taken off the 28 VDC input. These results were achieved despite the dual seriesed rectifier bridge which doubles the number of diodes and hence losses. (Dual bridge was employed to minimize rectifier stresses during their reverse recovery). The extra rectification losses were compensated by minimizing switching losses (resonant switching was demonstrated) and by careful design of the planar transformer. The efficiency would increase with increasing input voltage. With 100 Volts input, the anticipated efficiency is 94%.

A more detailed description of the converter and the dynamics of its interaction with the BTHT-200 thruster can be found in Ref. 6.


Table 2 Discharge converter major specifications

<table>
<thead>
<tr>
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<th>Nominal</th>
<th>Range</th>
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<tr>
<td>Input Voltage (Volts)</td>
<td>28</td>
<td>24 to 35</td>
</tr>
<tr>
<td>Output Voltage (Volts)</td>
<td>300</td>
<td>20 to 350*</td>
</tr>
<tr>
<td>Output Current (Amps)**</td>
<td>0.66</td>
<td>0 to 1.25**</td>
</tr>
<tr>
<td>Output Power (Watts)</td>
<td>200</td>
<td>0 to 400</td>
</tr>
<tr>
<td>Output Current Ripple (-)</td>
<td>&lt;5% Resistive Load</td>
<td>0.1 Amps p to p</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>50 kHz</td>
<td></td>
</tr>
</tbody>
</table>

*Operator selects V or I Control
**Short circuit protected to I_{max}

Fig 6 Discharge power converter efficiency versus output power

Fig 7 Discharge power converter efficiency versus output current

System Performance and Discussion

The thruster, cathode and converter were tested individually first and then integrated into a system. Both component and system level testing were carried out in Busek’s T6 facility described previously. The schematic of the experimental set-up is shown in Fig. 8. Most performance data were taken after thermal equilibration of the engine and thruststand which typically requires 30 minutes of steady state operation. The estimated error bars on thrust and mass flow measurements are ±2% and ±5% respectively.

Figures 9, 10, and 11 show the BTHT-200 system performance versus input power into the thruster (output power of the converter). The mass flows to anode and cathode and the tank pressure are specified in each figure. Thruster input voltage was held constant at 300 Volts. In Fig. 9 thrust ranges from about 4 mN at 100 W to 17 mN at 290 Watts.

Specific impulse (I_{sp}) and efficiency (η) were calculated using the measured thrust, mass flow and power and are presented in Figs. 10 and 11 respectively. Both anode and total I_{sp} and η are shown. The “anode” data exclude cathode power and flow and magnet losses. The “total” data include the cathode flow and all other losses except for the losses in the DC-DC converter.

Fig. 8 Schematic of the Experimental Setup

In the range from 100 to 300 Watts, the anode efficiency and I_{sp} varies from 20 to 45% and from 1100 to 1600 sec respectively. Including all losses lowers the efficiency by about 3 to 4% over the entire power range and lowers the I_{sp} by about 200 sec. Both the I_{sp} and η have a nearly linear dependence on input power from about 100 to 200 Watts. Above the 200 Watts the performance starts to approach an asymptote value reached at 300 Watts.
Fig. 9 Measured Thrust for the BTHT-200-X2B thruster with BHC-1500 cathode as the discharge power is varied from 100 to 300 Watts

Fig. 10 Specific impulse versus discharge power for the BTHT-200-X2B thruster operating with BHC-1500 cathode

Fig. 11 Efficiency versus discharge power for the BTHT-200-X2B thruster operating with BHC-1500 cathode
Performance tests were also conducted at a constant discharge power of 200 W while varying the discharge voltage and mass flow. Figure 13 shows that the thrust plotted versus applied voltage behaves as anticipated, increasing to a maximum of 12.5 mN at about 220 Volts. The thrust mass flow at this peak thrust point was \( \dot{m}_t = 0.96 \text{ mg/sec} \) yielding a measured maximum-thrust-specific-impulse \( I_{sp} = 1327 \text{ sec} \). The theoretical maximum thrust \( I_{sp} \) occurs at \(^8\)

\[
I_{sp} = \frac{2I_{ds} \sqrt{\Delta V_{id}}}{g \dot{m}_t \sqrt{2q/m}} = 1.68 \times 10^4 \frac{I_{ds} \sqrt{\Delta V_{id}}}{\dot{m}_t}
\]  

[3]

where \( g \dot{m}_t = 9.81 \text{ m/sec}^2 \), \( I_{ds} \) is discharge current, \( \dot{m}_t \) is thruster mass flow, \( q/m \) is the charge to mass ratio of the Xe ion and \( \Delta V_{id} \) is the total voltage loss in the thruster.

Equation [3] then yields \( \Delta V_{id} = 69.5 \text{ Volts} \) which is a typical value for this size thruster. Using the \( \Delta V_{id} \) and a primary electron loss parameter \( i \) which can be calculated from measured thruster efficiency \(^8\)

\[
\eta = \left(1 - i \right)^2 \left(1 - \frac{\Delta V_{id}}{V_{av}} \right)
\]

[4]

yielding \( i = 0.4 \), one can then calculate, with reasonable accuracy, the complete performance map of the thruster including the thrust and \( I_{sp} \) as a function of applied power and voltage. This procedure is of course applicable to any thruster. \(^9\)

The measured efficiency is shown as a function of discharge voltage in Fig. 14. It is notable that it peaks at a voltage below 300 Volts and remains at or above 40% anode efficiency over a broad range from 220 to 300 Volts.

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**Fig. 13** Thrust versus applied voltage for the BTHT-200 thruster operating with BHC-1500 cathode

**Fig. 14** Efficiency versus applied voltage for the BTHT-200 thruster operating with BHC-1500 cathode
The \( I_{eq} \) and efficiency of the BTHT-200 system compare favorably to published data from similarly sized thrusters. This includes the SPT-35, the SPT-50 and the Soreq thrusters. The SPT-50 has about the same “anode” performance but significantly lower “total” performance due to our low flow cathode. One would however expect the SPT-50 to have a higher “anode” performance because it is a substantially larger device operating at higher power than the BTHT-200.

The thruster and the cathode were delivered to the AFRL for further testing. The DC-DC converter remained at Busek. It is being used routinely in a continuing test program with various low power thrusters. It performs extremely well under various fault conditions including anode to cathode shorts and induced anode to ground arcing. The dynamics of the system is reported in a companion paper.

Conclusions

A novel, nominally 200 Watts Tandem Hall thruster, associated low flow 3.2 mm hollow cathode and a 400 W DC-DC discharge converter were successfully developed and demonstrated as an integrated system. The performance of the components and the integrated system compares favorably to similarly sized devices. Busek is now ready for low power Hall thruster flight demonstration program.

Acknowledgements

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References