Experimental Evaluation of a Green Bi-Propellant Thruster for Small Satellite Applications

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ABSTRACT

A bi-propellant thruster system based on the green propellants, nitrous oxide and propane, combines good storage density with specific impulse performance comparable to conventional space storable propellants. The non-toxic and self-pressurizing properties of nitrous oxide and propane yield a simple, safe, yet high performance system, suitable for CubeSats requiring moderate to large Delta-V maneuvers. The HT-PM400.10 propulsion system utilizes these propellants in a 2U subsystem, intended for 6U or larger satellites. Experimental results show that the system is capable of providing a total Delta-V of 231 m/s from a 1 N thruster. The thruster has demonstrated a combustion efficiency in excess of 94 % and peak-to-peak combustion stability of 1.3 % of the mean combustion pressure.

INTRODUCTION

Over the past several years, it has been widely recognized that the poor availability and low Technical Readiness Level (TRL) of CubeSat propulsion systems has hindered the development of advanced CubeSat missions. Current CubeSat chemical propulsion options typically require exotic propellants, which are hard to acquire, handle and/or export, resulting in high costs and barriers to use. The electric propulsion options, while providing excellent Delta-V performance using non-toxic propellants, often require long mission durations and prohibitively large power requirements to operate effectively. A system which can achieve both the simplicity of electric propulsion, while maintaining the ease of use and mission response time of a chemical system, will allow CubeSats to perform high Delta-V missions in a time and cost effective manner.

Hyperion Technologies produces a line of integrated Attitude Determination and Control Systems (ADCS) systems intended for CubeSats. Inclusion of a propulsion system will be the next level of integration to achieve a single solution for orbit determination and control.

The HT-PM400.10 propulsion module has been produced and tested under various conditions to verify its performance. The results of this testing and discussion of the implications for future CubeSat missions are presented in this paper.

Bipropellant thruster

A bipropellant thruster was selected for the HT-PM400.10 system as they provide high thrust levels in a compact package while requiring minimal power for a matter of seconds. This is in stark contrast to electric propulsion, which requires high power for extended periods. Bi-propellant systems can also achieve very small impulse bits, as well as high specific impulse and high thrust. High thrust enables the use of Hohmann transfer maneuvers, which require less Delta-V than spiral maneuvers and allow orbit raising to be completed within hours. This is a significant advantage over low thrust electric propulsion systems where a maneuver can take weeks or months to complete, consuming power and restricting the satellite’s attitude to the thrusting direction.

Propellant selection

Liquefied nitrous oxide and propane were selected as the oxidizer and fuel, respectively, for their ease of use and inherently safe properties. Both of these propellants are operated at their vapor pressure of 45 and 7.3 bar, respectively[1]. Both nitrous oxide and propane are non-toxic and disperse readily in a vented environment, thus, failure modes such as leaks are benign. They are easily procured without license nor subject to any export restrictions. There is no special equipment required and

[1] At 15 ºC bulk temperature

only minimal training is necessary for propellant servicing operations. This is in stark contrast to hydrazine, which requires extensive safety precautions such as SCAPE suits, dedicated filling facilities and specialized logistics (US Department of Health and Human Services, 1988).

The HT-PM400.10 system makes use of the propellants' self-pressurizing properties, reducing feed system complexity.

The theoretical specific impulse ($I_{sp\ vac}$) of the selected combination is in excess of 315s, which is comparable to current space-storable propellants such as hydrazine and nitrogen tetroxide (Schulte, 2003).

Nitrous oxide and propane provide a safe, simple and high performance propulsion option for CubeSats.

HT-PM400.10 CUBESAT PROPULSION SYSTEM

The HT-PM400.10 CubeSat propulsion system is a 2U propulsion subsystem. It consists of 2 major subassemblies, the tank module and the thruster. Both are produced using additive manufactured in 15-5PH stainless steel. Additive manufacturing of the tank module and thruster allow for system complexity to be seamlessly integrated into a single structural and functional piece.

As the propulsion system uses storable propellants and has a design life of five years or more[2].

Tank Module

The tank module contains the basic feed system and propellant storage and provides storage for 70 g of propane and 555 g of nitrous oxide for a total of 625 g of propellant.

The module contains all components necessary for standalone use such as service valves, filters, pressure relief valves and pressure transducers. The module feeds propellant to the thruster via high speed solenoid valves. Additive manufacturing allows for components such as filters and service valve bodies to be directly machined into place, dramatically reducing the number of seals in the feed system and thus the number of possible leak paths.

Propane is stored in a spherical fuel tank mounted inside a cylindrical nitrous oxide tank. The inner tank is structurally supported by a matrix, connecting the fuel and oxidizer tanks. This design allows the available space to be utilized much more effectively, increasing the total propellant mass and with it system performance.

Both tanks are designed to withstand 2x the maximum expected operating pressure (MEOP) and were hydrostatically tested up to 1.5x MEOP.

The corner rails of the tank module can be modified as required to accept any standard or custom CubeSat structure.

Thruster

The HT-PM400.10 thruster consists of an additively manufactured injector body with a conventionally machined nozzle (visible in Figure 5)[3].

The thruster is capable of operating at ambient temperatures between 0 and 30 °C. Figure 1 shows that within these temperatures, the thrust varies between 0.5 N and 1.5 N.

The thruster is mounted to two solenoid valves, which each require 2.1 W while the thruster is firing.

Nominal chamber pressure is 3.0 bar at an oxidizer-to-fuel ratio (O/F) of between 8.5 and 11.

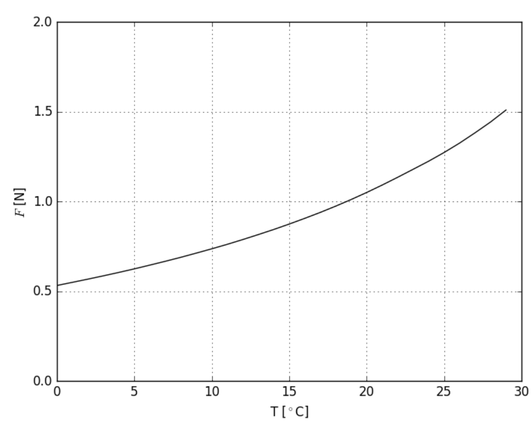

Figure 1: System thrust level varying with ambient temperature.

[2] To be verified through full system leak rate evaluation testing.
[3] The exchangeable nozzle is primarily used for testing purposes to allow for quick alterations. Fully printed chamber and nozzle versions have also been successfully tested.

Nitrous oxide is passed through a regenerative cooling cycle inside the injector body to cool the spark igniter and pressure sensor bodies. The downstream volume of the feed system has been minimized to achieve small impulse bits with minimal propellant waste at motor startup and shutdown.

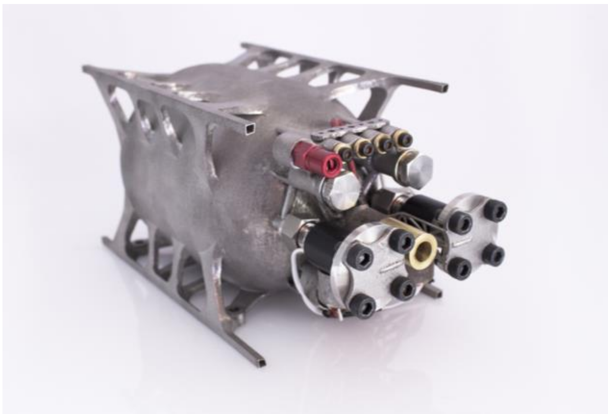

Figure 2: The HT-PM400.10 propulsion system.

The system requires 6 W during operation and <0.1 W during sleep. The system can be woken and fired within seconds.

Measurement setup

To monitor the health and measure the performance of the propulsion module, five pressure sensors and five thermocouples are used. The module is also weighed before and after each test to determine total propellant consumed.

Pressure sensors measure the tank and injector inlet pressure of each propellant, as well as combustion pressure. The pressure sensors are a compact piezo resistive type allowing for high accuracy in a very small package. Thermocouples measure the temperature of the injector body, nozzle outer wall at the throat, valve outlets and the centre pressure sensor housing on the thruster.

RESULTS

The thruster performance parameters presented in this section were determined at an ambient temperature of 10 ºC. The thruster is fired with the nozzle pointing upwards at ambient pressure of approximately 1 atmosphere. Vacuum performance is then extrapolated from the atmospheric test data. The propellant feed pressures are inherent to the liquefied propellants used and follow from the ambient temperature of 10 ºC to be 40 bar and 6.4 bar for nitrous oxide and propane respectively. All results are summarized in Table 2.

c* efficiency and $I_{sp\ vac}$

The thruster's combustion performance, c* efficiency, is assessed based on the ratio between the experimentally achieved combustion pressure and theoretical maximum combustion pressure for a given value of total mass flow, mixture ratio, and nozzle throat area. From the experimentally determined c* efficiency, the $I_{sp\ vac}$ can be determined for a 60 % truncated bell nozzle with an expansion ratio of 100.

The total mass flow is determined weighing the entire system before and after a 10 s burn. This process is repeated 4 times.

The c* efficiency was found to be 94 %. From this value, a specific impulse of 290 s is calculated based ion the aforementioned nozzle parameters.

Burn behavior

Figure 3 displays a typical burn of 2 s duration. From this graph, it can be seen that fuel flow precedes oxidizer flow by 150 ms. Ignition occurs 30 ms after oxidizer flow is initiated. The chamber pressure then rises to >95 % maximum pressure within 30 ms, after which the motor burns consistently until T + 2 s. Shutdown is completed within 20 ms although fuel flow takes a further 80 ms to fully empty. This graph shows that some fuel is lost unburnt with each startup and shutdown, equivalent to approximately 150 ms of runtime. This equates to a total of 0.0042 g of propane per startup/shutdown sequence. Over the course of 1000 firings, a total of 4.2 g, or 0.67 % of total propellant is lost due to startup and shutdown behavior. This is considered an acceptable loss.

From Figure 3, the combustion stability is found to be ±1.3% of the mean combustion pressure. This is considered a stable operating mode (Sutton, 2001). The combustion pressure is also found to decay negligibly over the course of the 2 s burn.

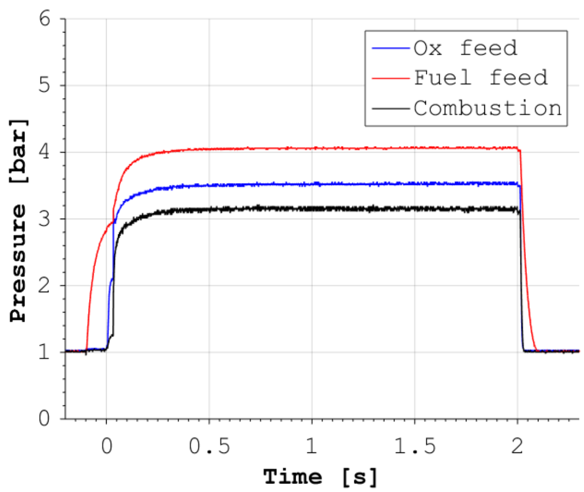

Figure 3: A typical 2s burn.

Minimum impulse bit.

The minimum impulse bit is defined as the total impulse of a burn where 50 ms of stable operation is achieved after startup to >95 % of maximum combustion pressure. Typically, startup required 30 ms, hence the total burn duration is 80 ms. The minimum impulse bit can be further reduced from the quoted values if the stable operating time is reduced below 50 ms. As a more extreme measure, the thruster can be operated in oxidizer or fuel cold gas mode to achieve an impulse bit 10x or 100x smaller respectively.

Maximum impulse bit and duty cycle

The maximum impulse bit is determined by allowing the motor to run until the nozzle reaches its maximum allowable operating temperature of 500 ºC or until the pressure sensor bodies reach above 100 ºC. It was found that a burn time of 15 s is achievable within these parameters. The duty cycle of the motor then follows from the time required to cool the motor between maximum impulse bit firings, which is found to be 750 s. It is to be noted that the cooling rates will change in vacuum.

Repeatability

Figure 4 demonstrates the repeatability of the minimum impulse bit. This figure displays 3 firings, all conducted within 10 s of each other. Of 10 such firings, the average impulse bit was found to be 0.075 Ns with a standard deviation of 0.00122 Ns.

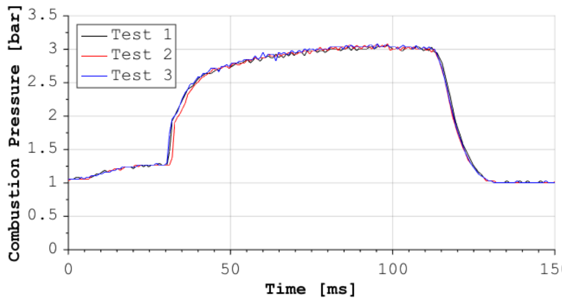

Figure 4: Demonstrated repeatability in 3 minimum impulse bit pulses.

Table 1: Summary of experimentally demonstrated performance parameters (ambient temperature = 10º C).

Parameter	Value
Thrust	0.75 N
c* efficiency	94 %
Isp $_{vac,\ Ae/At = 100}$	290 s
Min impulse bit	0.075 Ns
Max impulse bit	11 Ns
Max duty cycle	2 %

Total impulse

It is known that 625 g of propellant can be stored on board. 98 % propellant utilization is expected. From the demonstrated c* efficiency and total propellant stored, the total impulse is determined to be 1750 Ns.

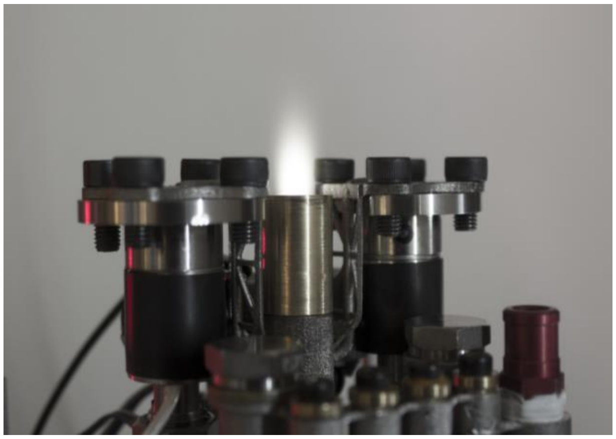

Figure 5: Thruster firing.

Restart performance

Throughout the course of testing, the thruster was restarted over 100 times with no measurable degradation of the throat, spark plug, or other thruster components. It is expected that thousands of starts are possible. Future tests will confirm this.

MISSION APPLICATIONS

The HT-PM400.10 CubeSat propulsion system can be used in a variety of missions. This section outlines the theoretical performance capability in terms of satellite maneuvers for a 6U, 8 kg CubeSat, derived from the thruster the experimental data presented in the previous section.

Orbital elements change

From the experimental data, it is found that a total impulse of 1750 Ns can be achieved from 625 g of propellant. For an 8 kg satellite, this results in 231 m/s of Delta-V. Table 2 shows that a circular orbit can be raised from 400 km to 830 km, or an inclination change of 1.73 ^{0} can be achieved. It follows from the minimum and maximum impulse bits that the corresponding single-burn apogee raises are 0.03 and 4.8 km respectively.

Table 2: Possible maneuvers for a 6U, 8kg satellite from a 400km circular orbit with the HT-PM400.10 propulsion system.

Orbital parameter	Value
Max. apogee raise from 400km circular	1285 km
Total Inclination change	1.73^{0}
Max. apogee raise per orbit (single burn)	4.9 km
Min. apogee raise raise per orbit (single burn)	0.03 km

Drag compensation mission

CubeSats often fly at altitudes where they incur significant aerodynamic drag, causing them to re-enter the Earth's atmosphere within months or even weeks. In the example mission shown in Figure 6, an 8kg, 6U satellite decays from a circular 320 km orbit. In the first case, the satellite is able to re-raise its orbit whenever it drops to 315 km, approximately every 12 days. It is able to do this until it finally runs out of propellant on day 1050 at which point it decays back to Earth in a further 85 days, as in the un-propelled case. This figure shows that the mission life at a given altitude can be extended by factor of 13. This factor remains roughly constant at lower altitudes. For particularly low altitude missions, the HT propulsion system can significantly increase the mission life. The simulation presented in Figure 6 is based on the COSPAR atmospheric model and takes into account cyclic solar activity (Committee on Space Research, 2012).

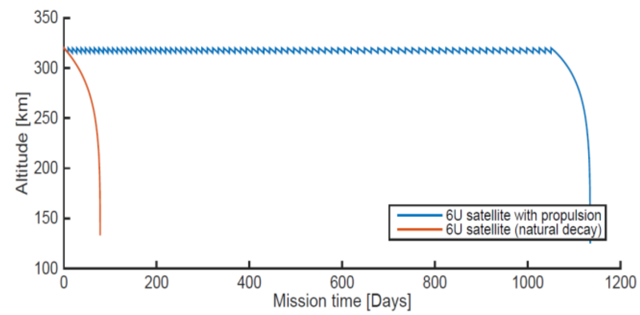

Figure 6: Natural orbit decay of a 6U satellite vs extended mission using a HT-PM400.10 propelled 6U satellite. Atmospheric conditions representative for a mission begin in July 2017.

FUTURE WORK

The testing presented in this paper shows that the thruster performs well in the middle of its operating range. These properties have yet to be determined at the extreme operating temperatures of the system. Future testing will include performance evaluation at ever more extreme cold and hot temperatures to find the absolute operating limits of the thruster. The ignition system is designed to be capable of thousands of starts. This must be properly stress tested in future work.

Future testing will be conducted in a vacuum chamber to directly measure thrust, as well as observe any changes in startup performance, maximum impulse bit and duty cycle. Testing will conclude with a flight test of a demonstrator model if the opportunity arises.

In terms of hardware, future work will include further refinement of the tank module to increase propellant storage and therefore total Delta-V performance. The thruster body and nozzle will also be manufactured in a single piece and in high temperature alloys to allow for larger maximum impulse bits. These developments are expected to be completed in late 2016.

The propulsion system presented in this paper is intended to operate in conjunction with Hyperion Technologies ADCS systems. Future models will work to integrate the

Hyperion iADCS400 system with the HT-PM400.10 thruster to provide a standalone ADCS and GNC solution for CubeSats.

CONCLUSION

The HT-PM400.10 CubeSat propulsion system has been experimentally characterized over a series of tests. The 1 N thruster utilizes the safe, common and non-toxic propellants nitrous oxide and propane, allowing for simple and cost effective operation while providing I_{sp} performance well in excess of conventional storable monopropellants currently being developed for CubeSats (Carpenter, 2013).

The system was found to provide a Delta-V of 231m/s to a 6U CubeSat whereby 2U is reserved for propulsion. The thruster has demonstrated combustion efficiency of 94% and combustion stability of +/- 1.3% of the mean combustion pressure. A minimum impulse bit of 0.075 Ns was found with a standard deviation of 0.000122 Ns.

The high thrust rating of 1 N enables maneuvers to be performed quickly and efficiently. The total system performance is sufficient to raise a circular orbit from 400 km to 830 km or perform an inclination change of 1.73 degrees on a 6U CubeSat. The system can alternatively extend the mission lifetime of a 6U CubeSat at 320km altitude by a factor of 13.

The additive manufacturing process used allows for a high level of customization to suit any standard or custom CubeSat structure, or larger Delta-V budgets. The HT-PM400.10 system will be continuously improved over the coming year and made available to enable high Delta-V CubeSat missions to become reality.

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