A Monopropellant Milli-Newton Thruster System for Attitude Control of Nanosatellites

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Abstract. Work is progressing on monopropellant thrusters for use as an attitude control system for nanosatellites (satellites whose mass is under 10 kilograms). The thrust range for these microthrusters is on the order of milli-newtons. Systems using both hydrazine and hydrogen peroxide are being developed which will offer higher performance than currently available thrusters for nanosatellites. Complete thruster systems using both propellant combinations have been built and are undergoing evaluation. Hot firings are currently being conducted. The microthruster system will be tested on an upcoming nanosatellite to be launched at the end of this year. These thrusters will offer an inexpensive, high performance option for attitude control for nanosatellites or fine pointing control for small satellites.

Introduction

Microthrusters for nanosatellites are needed to provide attitude control and pointing capability. Currently the state-of-the-art in thruster systems for nanosatellites is cold gas systems. These systems provide relatively low performance and are prone to leakage and their high operating pressures require massive tank structures. There are currently no available hydrazine monopropellant thrusters available for spacecraft in the 1 to 20 kg range. [1] Small, high-performing, thruster systems would enable greater capability for nanospacecraft to explore asteroids, comets, Mars and its moons among other missions. These thrusters also have military uses on nanospacecraft currently under development by the military.

Micro Aerospace Solutions (MAS) is currently funding the development of both hydrazine and hydrogen peroxide monopropellant microthrusters with a thrust level in the milli-newton range. The object of this is to create a thruster to be flight tested on a nanosatellite currently being built by MAS.

The very small size of the thruster allows an impulse bit small enough to provide fine attitude control of nanosatellites. A complete thruster nanosatellite attitude control system preliminary design has been created and analyzed.

Hydrazine is a toxic, carcinogenic propellant that requires special handling procedures and pre-cautions. For these reasons, the hydrogen peroxide system offers an excellent choice for university and other school-based nanosatellite programs to have thruster attitude control on-board. Hydrogen peroxide is non-toxic, can be diluted with water and does not pose the health problems of hydrazine. With careful system cleaning and choice of materials, hydrogen peroxide's capability to self-decompose can be controlled for a nanosatellite mission duration of about one year.

Thruster Design

MAS has developed a basic microthruster thrust chamber. The design is being refined for ease of construction and final design parameters are currently being analyzed by software.

Most hydrazine thrusters use a catalyst bed made from iridium impregnated alumina pellets 1.5 to 3 mm in diameter. Clearly such a catalyst bed is too large to be practical for this thruster design. An innovative alternative was developed using iridium or platinum-iridium mesh. An iridium-mesh catalyst is wound out of a flat sheet and placed inside the chamber. This allows a large catalytic surface area in a small volume. The catalyst is created with a length to diameter ratio of 2:1 as was done by Parker et al. [2] Hydrazine enters through the inlet, is catalyzed by the iridium and the exhaust exits through the convergent/divergent nozzle. Figure 1 is a drawing of the chamber.

The length of the thruster is 0.200 inches, the exit diameter of the nozzle is 0.150 inches and the throat diameter is 0.015 inches. This gives ε, the area ratio, to be 100. Stainless steel 316 is used for the chamber to withstand both hydrazine and the high temperature reactant gas. A chamber with threads inside was created for testing to allow various injector elements to be tested in the system.

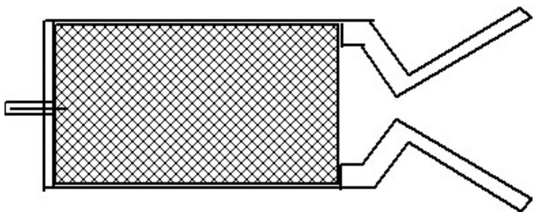

Figure 1 Monopropellant Microthruster Basic Thrust Chamber Design

The challenges involved in the design include machining the very small nozzle area and maintaining the divergence angle of the nozzle. The injector is simply a capillary tube insert that can be welded into place.

Important parameters still to be tested include the proper catalyst mesh size, the interior volume of the chamber for proper propellant dwell time and the nozzle geometry to compensate for the boundary layer and viscous effects present in low-Reynolds-number flows common to micronozzles.

Hydrogen Peroxide Thruster

The basic hydrazine thruster design was then taken and modified for a hydrogen peroxide thruster. Although hydrogen peroxide is lower performing than hydrazine, its relatively benign nature makes it ideal for many small satellite applications. The catalyst is wound out of pure silver mesh. Thrust chambers can be fabricated out of brass, as is used on the hydrogen peroxide thrusters developed by Whitehead. [3] The thermal expansion rate of brass closely matches that of silver so as the chamber heats up both the chamber and catalyst expand at a similar rate. Brass also has the advantages of being easily machined and of having high strength. Due to the melting points of both pure silver and brass, the concentration of hydrogen peroxide is kept at a maximum of 85%.

MAS is working with FMC Industrial Chemicals corporation to provide 85% pure, propulsion grade hydrogen peroxide for further tests. Current tests with peroxide are being done with peroxide distilled from 35%, low stabilizer, lab-grade peroxide. Catalyst performance has been excellent with little evidence of poisoning from impurities. Also, firings of the thruster have produced consistent decomposition implying the catalyst activity is consistent. The catalyst mesh requires warming to get to an operating temperature so the first few pulses of the valve during a cold start are used to initiate the decomposition and heat the catalyst mesh.

Due to the relatively easy handling and environmental requirements and the low-cost manufacturing and component costs, the hydrogen peroxide system offers a very good alternative to nanosatellite developers on limited budgets. This could be especially beneficial for universities and other school-based nanosatellite programs currently under development. It is also possible that a table-top rocket propulsion test bed could be created to demonstrate rocket engineering to university students in a safe environment. This is similar to small jet engine trainer/experimentation systems that are available today.

Propulsion System Tests

A basic thruster verification test system has been created. A stainless steel sphere, 2 inches in diameter, is used as the propellant tank. Figure 2 shows a prototype tank in sections. Nitrogen or helium will be used as the system pressurant. The pressurant gas will force the propellant into the thrust chamber when the micro control valve is opened. This type of blowdown pressurization system has been used successfully on spacecraft for many years. It offers simplicity but with the problem of a slow decrease in feed pressure over the lifetime of the system which should not be a major concern for a proof of concept demonstration system.

Since the viton bladder will provide a barrier between the pressurization gas and the hydrazine or hydrogen peroxide propellant, nitrogen can be used as a pressurant. This removes the concern that nitrogen gas dissolved in the propellant could lower performance or cause gas bubbles. Use of nitrogen instead of helium as a pressurant also has the advantage of the system being less susceptible to leaks. An added advantage of this system is a lower pressure being needed for pressurization and no need for a separate pressurization tank or regulator. This will save valuable mass and volume on a nanospacecraft as well as lowering overall system complexity. Check valves should be used in the system to ensure no reverse flow as well as filters placed downstream of fill and check valves to capture any possible particulates. Also, very special care must be taken for cleanliness in the entire system so that the extremely small tubes in the system do not clog.

A key element to any thruster system and an area that needs more research is micropropulsion valves. Presently, three hydrazine compatible prototype micro-dispense valves have been purchased from the Lee Valve Company for testing in our prototype system. These are microfluid-dispensing valves which have been modified to withstand pressure of more than 120 psi, see Figure 3. Future valves will be capable of being operated up to at least 300 psi. Even such a small size of approximately 0.83 inches x 0.22 inches may be too large for certain nanosatellite applications. Without any redundancy at least 12 valves will be required for a typical nanosatellite system, one for each thruster. These valves are the smallest production-based valves that could be found and also have a reasonable cost of $200 each. They require an average power of 500 mW.

A complete spaceflight microthruster-based propulsion system has also been designed, see Figure 4. This uses either a 2 or 3-inch stainless steel tank depending on propellant volume required for the mission. A viton bladder is placed separating the two halves of the spherical tank for gas-pressurant isolation and zero-gravity propellant feed capability. The tank halves are then sealed This design will ensure that propellant is expelled to the thruster in any orientation in space. A complete prototype single thruster system with 2-inch tank, valve, check valve and filter has a mass of 60 grams and a complete 12 thruster system can be built for a mass under 120 grams.

Initially, the tank may be pressurized to 200 psi. Through the use of the blowdown technique, the end-of-life pressure may drop to about 50-75 psi, causing a lower impulse bit at end of life than at the beginning. If more spacecraft mass is available, a high-pressure gas tank with regulator could be fitted to ensure consistent performance throughout system life.

The prototype single thruster system has been built and is currently undergoing firing tests with hydrogen peroxide. Once performance is satisfactory, another identical system will be built for use with hydrazine.

This will allow two distinct propulsion option for nanosatellite attitude control systems. For high performance requirements, the hydrazine system can be used. For a non-toxic, cheaper alternative, the hydrogen peroxide system can be used.

Issues with storability have to be addressed. However, since the mission lifetime of most nanosatellite missions is under one year, hydrogen peroxide decomposition in a tank should not be a major issue.

Figure 2 Propellant Tank Halves

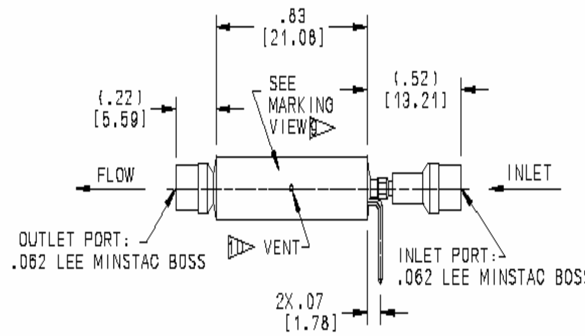

Figure 3 Lee Micro Solenoid Valve

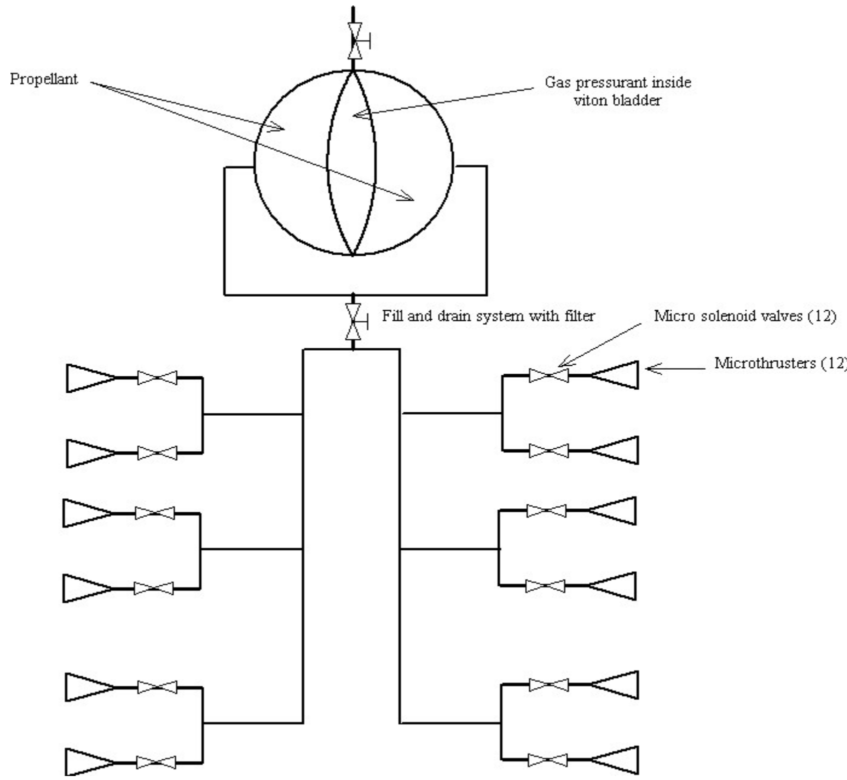

Figure 4 Microthruster System Design

Performance

A baseline nanosatellite mission for a 10 kg spacecraft [4] was analyzed to compare to the capabilities of the MAS microthruster. The MagCon nanosatellite constellation is designed to use nanosatellites with mass of no more than 10 kg to observe the Earth's magnetosphere environment. The attitude control parameters for this mission are 2.4 N-s total impulse, input power below 1 watt, specific impulse of 60 seconds and minimum impulse bit of 0.044N-s.

Mueller defined some minimum impulse bits required for typical microspacecraft missions. For a 10 kg spacecraft I-bit would be 1.4 x 10^{-4} N-s for a firing duty cycle of 1/20 Hz and 1 degree pointing. [1]

The Lee micro-solenoid valves used in this design are capable of delivering less than 10^{-4} grams/sec of hydrazine to the chamber at 100 psi. Specific impulse, I_{sp}, is taken to be 150 sec.

This value is low for a hydrazine thruster but it takes into account boundary layer and viscous losses in a micronozzle. Assuming this mass flow rate as the mass of the minimum impulse bit possible, m_{Ibit}, the minimum impulse bit, I_t can be found using equation 1, where g_0 is the gravitational constant: [2]

$$I_t = m_{Ibit} I_{sp} g_0 \qquad (1)$$

For this system the minimum impulse bit is 1.715x10^{-4} N-s. The hydrazine milli-Newton thruster described here could be used for either Impulse bit requirement.

Using a 2-inch (5.08 cm.) tank, total propellant on board would be approximately 30 milli-liters. Assuming Mueller's mission requirement of 1 pulse every 20 seconds, this would provide an operational life for propellant consumables of about 1.75 years. The 3-inch (7.62 cm) tank could provide the possibility of 650,000 thruster pair firings for attitude control. Table 1 summarizes these parameters. To keep hydrazine from freezing heaters may be used. If the heaters are not active while the thrusters are firing the 1.2 maximum watt power usage can be maintained.

Table 1 Propulsion System Parameters

Tank Diameter (cm)	Propulsion System Mass (kg)	Thruster couple firings	Power (watts)
5.08	0.110	143,250	1.2
7.62	0.150	650,000	1.2

Past Efforts

The microthruster system described here is one of the smallest monopropellant microthruster systems known using hydrazine or hydrogen peroxide in a flight configuration.

Previous work has been done in the lab on MEMS thrusters but none have resulted in a flight design. [5] MEMS systems have a drawback of typically having to be made of silicon, which is not compatible with propellants such as hydrazine. Progress is being made in their development but flight-ready systems are still in the future.

Other studies have described warm gas systems that require the use of nitrogen/hydrogen/oxygen gaseous mixtures requiring heavy tanks. [6] Cold gas systems have been often used in micro- and nanosatellite designs but their relatively high mass, leak rates and low performance are disadvantages. Systems have been proposed using butane. [7] However, this system is for main propulsion and is of a much larger scale.

The simple, low-cost design presented here is approaching flight capability. It is hoped that the entire system will be operational and ready for spaceflight qualification by the end of 2002. Further refinements and design changes may take place in the future as a better computational handle is gotten on fluid flow in micronozzles. [8]

Conclusion

A low-cost, monopropellant microthruster system is under development. It is envisioned as an attitude control system for nanosatellites. Both higher-performing hydrazine and more benign hydrogen peroxide systems are currently being designed and tested. An innovative catalyst has been designed using mesh material wound into a spiral pattern. An analysis of the hydrazine system indicates a minimum impulse bit of 10^{-4} N-s.

The complete thruster propulsion system is composed of micro-dispense valves from the Lee Company, a small 2 or 3-inch tank with a viton positive expulsion bladder and filters. This system can deliver 143,250 thruster-couple firings for the 2-inch tank version or 650,000 firings for the 3-inch version. A flight-ready system is anticipated by the end of 2002.

Uses of the system include nanosatellite science missions, communications swarms, university nanosatellites and military applications. The hydrogen peroxide version could also be used to demonstrate rocket propulsion fundamentals in a university laboratory setting.

Acknowledgements

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