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Development of Busek 0.5N Green Monopropellant Thruster

Michael Tsay, Derek Lafko, Jurg Zwahlen, William Costa
Busek Co. Inc.
11 Tech Circle, Natick, MA 01760-1023; 508-655-5565
mtsay@busek.com, dlafko@busek.com, jurg@busek.com, wcosta@busek.com

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ABSTRACT

The monopropellant community has been actively pursuing low toxicity, "green" monopropellants for the past two decades. Of the large number of formulations developed, AF-M315E has received the most attention in the U.S. In comparison with hydrazine, AF-M315E offers improved Isp and density-Isp while being extremely stable and easy to handle. Despite the potential benefits, development of AF-M315E thrusters has been slow due to the lack of suitable catalysts. Busek is pioneering an alternative catalytic reactor to address such issue. Busek has developed a 0.5N-class AF-M315E thruster that has demonstrated 20+ minutes of cumulative life and consistently performs at a c* efficiency in the range of 89-93%. A piezoelectric microvalve for the 0.5N thruster has also been developed. It is superior to state-of-the-art solenoid valves of similar flow level as it requires only 0.5W of power and weighs a mere 67 gram. Potential commercial applications for the 0.5N thruster are abundant, including but not limited to primary propulsion for NanoSats and ACS propulsion for SmallSats. Scaling up the thruster is feasible and will create more opportunities to compete with legacy hydrazine thruster systems in the future.

INTRODUCTION

Since the late 1990's, there have been several efforts to develop high-performance, non-toxic monopropellants for the replacement of hydrazine. These "green" monopropellants typically are single-phase, very concentrated solutions consisting of a soluble oxidizer and a fuel. Some of them have slight water content for desensitization against explosion. A great number of formulations have been proposed based on energetic oxidizers such as hydroxylammonium nitrate (HAN), ammonium dinitramide (ADN), hydrazinium nitroformate (HNF) and ammonium nitrate (AN).[1,2,3,4] Propellants based on HAN have received the greatest interest in the United States, ADN in Sweden, and HNF in the Netherlands and Germany. AN is usually regarded as an inferior choice among the four due to its low solubility and energy content.

Motivation

This work was motivated by the need of a small, non-toxic chemical thruster that can be used by developers of NanoSats or SmallSats. As these miniature satellites grow in functionality, their applicable missions seem to be limited only by the lack of propulsive capability. Small monopropellant thrusters offer the simplest solution from the perspective of system complexity and power consumption. Among the few monopropellant selections, legacy systems using hydrazine are not desirable for search institution work due to the many toxic and physical hazards that hydrazine poses.

The emerging green monopropellants are regarded as the best alternatives to hydrazine. They are safe and stable that handling requires minimum personal protective gear. Spill-related hazards are also less of a concern. Green monopropellant systems can easily be stored on the shelf in a fully-loaded state, which drastically simplifies spacecraft integration and launch preparation.

What is AF-M315E?

AF-M315E is a green monopropellant formulated by the U.S. Air Force Research Laboratory (AFRL) specifically for space propulsion.[5] Its origin can be traced to the U.S. Army's development of liquid gun propellants, which did not prove suitable for the relatively low combustion pressure in rockets.[6] AF-M315E is ultra stable and shock resistant, yet when fully decomposed it can produce an adiabatic flame temperature close to 1800°C.[5] Compared to hydrazine, whose flame temperature does not reach much above 1000°C, AF-M315E offers approximately 13% increase in specific impulse (Isp) and 63% increase in density-Isp.

Combustion of AF-M315E

Similar to other monopropellants, decomposition of AF-M315E is facilitated by a catalytic reactor. When cold, the reactor needs to be pre-heated to a temperature threshold before full decomposition can occur. Once the decomposed propellant is ignited the heater can be turned off. The reactor is kept hot via thermal soak-back from the main combustion.

The pre-heating requirement of the reactor varies with design, but generally it is much higher than that of a hydrazine type. Ignition can fail if the reactor does not reach temperature, or if the propellant flow rate exceeds the reactor's designed loading. In either case the result is known as quenching, which is characterized by partial decomposition of the propellant but without combustion. The exhaust of a quenched reactor is a dense, white smoke and is usually accompanied by droplets of unused propellant. In contrast, successful ignition of AF-M315E generates intense heat and produces an exhaust that is almost invisible to the naked eyes. Figure 1 shows both examples of failed and successful ignition. These pictures were taken with Busek's stationary combustor during the early-stage of its thruster development.

It is worth mentioning that finding a suitable catalyst for AF-M315E has always been a challenging task. Previous research has shown that catalysts designed for hydrazine would quickly deteriorate when subjected to the high flame temperature of AF-M315E. The failure mechanism is apparently due to material sintering and substrate disintegration, which can lead to very limited thruster lifetime as well as continuous performance reduction. These problems are similar to the ones often observed in larger hydrazine thrusters.[7] To this day catalyst attrition remains a key obstacle to general application of AF-M315E.[5] Busek's solution to the catalyst problem represents a major breakthrough in green monopropellant technology.

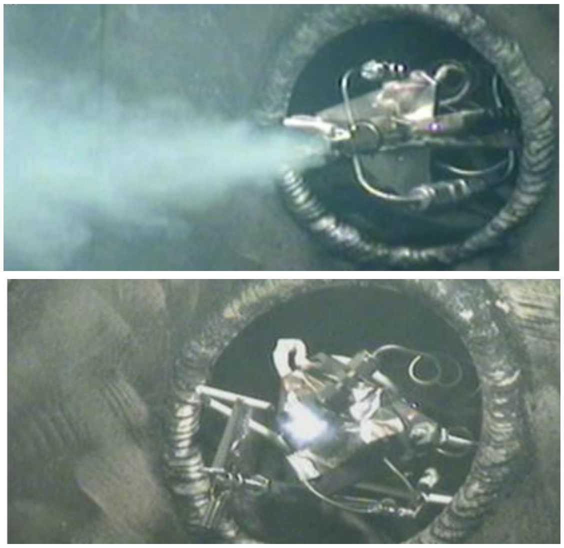

Figure 1: (Top) Failed Ignition Due to Quenched Reactor; (Bottom) Successful Ignition in Busek's Stationary AF-M315E Combustor

BUSEK 0.5N AF-M315E THRUSTER

Busek's AF-M315E thruster utilizes an innovative catalytic reactor that can withstand its harsh combustion environment. Unlike typical monopropellant reactors, Busek's invention features a patent-pending, monolithic design that does not require ceramic-supported catalysts or bed plates for catalyst containment. The reactor design was demonstrated and fully characterized in a stationary combustor (Figure 1) prior to implementation in the 0.5N thruster. An early prototype version of the thruster is shown in Figure 2.

Figure 2: Prototype Version of Busek 0.5N Thruster

Hot-Firing Tests of Prototype Thruster

The prototype thruster underwent extensive hot-firing tests. Figure 3 shows one of the tests. Approximately 15W of power is needed to pre-heat the reactor to its operating temperature. As mentioned previously, the heater can be turned off once ignition is achieved.

Figure 3: Hot Firing of Prototype 0.5N Thruster

One focus of the hot-firing tests was to investigate the onset of AF-M315E ignition with respect to the reactor's pre-heat temperature. A thermocouple was attached to the thruster body for recording its equilibrium temperature before propellant was first injected. This pre-firing equilibrium temperature was controlled by varying the heater power. Table 1 shows the ignition results. At 355°C, the thruster failed to ignite and produced a large plume of white smoke. In the 370-390°C range, ignition occurred after a short pulse (<1sec duration) of smoky exhaust was observed. This phenomenon is referred to as slow start. At 395°C, traits of slow start have diminished to barely noticeable, indicating the onset of successful ignition. Above 400°C reliable ignition was repeatedly obtained.

It should be noted that the external thermocouple's reading may not accurately represent the internal temperature of the reactor (hence the notion of estimated temperature in Table 1). The true pre-heat requirement of the reactor, therefore, should be slightly lower than the reported onset value of 395°C.

Table 1: Thruster Ignition vs. Reactor Temperature

Test #	Estimated Reactor Pre-heat Temp, °C	Ignition?
1	355	Fail
2	374	Slow Start
3	386	Slow Start
4	395	Onset
5	400	Success
6	424	Success

Performance of Prototype Thruster

The prototype 0.5N thruster was test-fired in the laboratory with a syringe pump feed system. The positive-displacement pump helped obtain the characteristic velocity (c*) measurement by providing a known propellant flow rate. The thruster's combustion performance was then assessed by its c* efficiency, which is defined as the ratio between measured and theoretical c*. Due to limited fuel reservoir in the syringe pump, each hot firing was restricted to approximately 60sec in duration at full throttle. Throttling is possible between 20% and 100% of the designed flow.

Figure 4 demonstrates the throttle-ability of the thruster. Following successful ignition, the combustion chamber in this example reached ~310psia with 100% propellant flow. At the 60sec mark, the propellant feed was throttled down to 50%, resulting in a reduction of combustion pressure to exactly half of its peak value. The "fuel line" pressure shown in Figure 4 was measured downstream of the syringe pump but just upstream of the fuel injector.

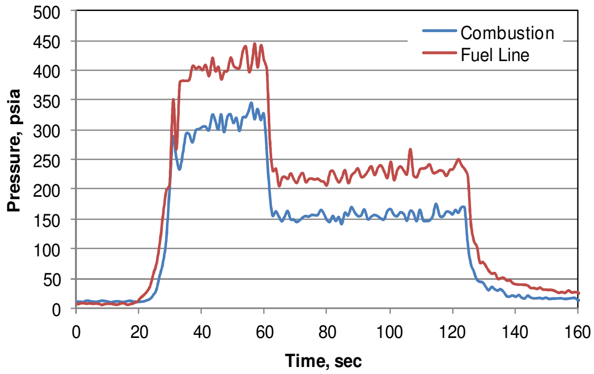

Figure 4: Combustion Data from Throttling Demo; 100% Flow Transitioning to 50% at 60sec-Mark

To date, 100-400psia combustion pressure has been demonstrated with the prototype thruster. A combination of throat sizing and flow throttling was used to achieve this wide pressure range. At the nominal operating pressure of 200psia, 89-93% c* efficiency was consistently obtained.

Post-Test Examination of Catalytic Reactor

During the prototype thruster development, one particular configuration of the catalytic reactor was subjected to 20 hot firings with 20+ minutes of accumulated run time. No reduction in c* performance was observed during that period. Upon the conclusion of these tests, the reactor was taken out for degradation analysis. From visual inspection the reactor seemed intact without any material or structural damage. Precision scale measurement then confirmed no loss in overall mass. Subsequent elemental analysis using a scanning electron microscope (SEM) showed that there was no oxide presence and the element spectrum was nearly identical to the one of the pre-test assembly. The SEM result is shown in Figure 5.

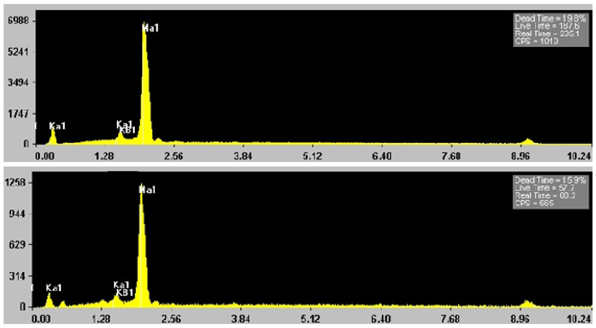

Figure 5: SEM Analysis of Elemental Spectrum for Pre-Test (Top) and Post-Test (Bottom) Reactor

Although a more thorough investigation is needed, Busek's reactor so far has exhibited all characteristics of a catalyst capable of long life. It has also demonstrated the ability to suppress, if not eliminate, the continuous performance degradation issue that has plagued so many other types of monopropellant catalysts.

Fabrication of High-Performance Micro Nozzle

In the early days of development, it was noticed that the actual thrust produced by each prototype thruster (few units were made) was not consistent despite similar c* performance. The investigation led to cold-gas thrust calibration of each micro nozzle used. It was soon discovered that because of its small scale, tiny machining imperfection on the nozzle throat could have great impact on the nozzle's flow efficiency. Possible sources to blame include throat concentricity, surface roughness, and sharp transition to the exit cone that could cause undesired flow separation.

To overcome problems related to machining imperfection, Busek has developed a cost-effective way to post-process the micro nozzles. The result, shown in Figure 6, gives a smooth surface finish around the throat. The transition from the throat to the exit cone also gets rounded, which helps guide the flow into the expansion zone. From experience, the throat concentricity has to be within 5% of its diameter for the nozzle to have a chance to achieve >90% efficiency.

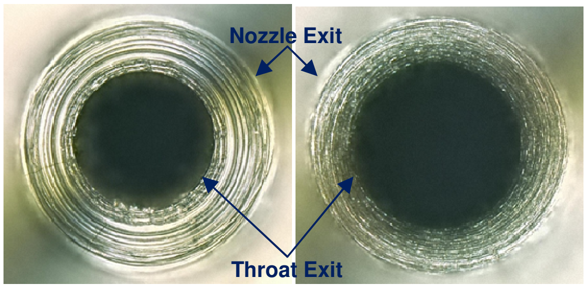

Figure 6: (Left) Machined Nozzle Showing Sharp Edge on Throat Exit; (Right) Post-Processed Nozzle Showing Smooth and Blended Throat Exit

The effectiveness of the developed post-processing technique was demonstrated via cold-gas thrust calibration. The performance indicator used here is the cold-gas nozzle efficiency (μ_{nozzle}), calculated from the specific impulse equation shown in Eq. 1. Finding μ_{nozzle} requires the knowledge of thrust (T), chamber temperature (T_0), expansion pressure ratio (P_{exit}/P_0) and mass flow rate ($\dot{m}$). In this case, T is measured directly, T_0 is assumed 293K, and P_{exit}/P_0 is a variable parameter with P_{exit} assumed 14.7psia for atmospheric and 0psia for vacuum tests. The required mass flow rate $\dot{m}$ is acquired from the characteristic velocity equation shown in Eq. 2, where P_0 represents the chamber pressure and A_t is the throat area. The c* efficiency (μ_{c*}) term in Eq. 2 is assumed 100% for cold-gas flows.

$$I_{sp} = \frac{T}{\dot{m}g} = \frac{\mu_{nozzle}}{g}\sqrt{\frac{2kRT_0}{k-1}\left[1-\left(\frac{P_{exit}}{P_0}\right)^{\frac{k-1}{k}}\right]} \qquad [1]$$

$$c^* = \frac{P_0A_t}{\dot{m}} = \mu_{c*}\frac{\sqrt{kRT_0}}{k\sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \qquad [2]$$

The cold-gas thrust calibration was conducted with nitrogen gas at 140-200psia chamber pressure. The calculated efficiency for one of the finished micro nozzles is shown in Figure 7. It is no surprise that the atmospheric nozzle efficiency is highly dependent on the chamber pressure (or pressure ratio to be exact). The vacuum nozzle efficiency, on the other hand, is indifferent to such parameter as the theory predicted. Evidenced in Figure 7, the post-processing technique helped the micro nozzle achieve 94% nozzle efficiency in vacuum. The data have ±2% uncertainty due to errors in pressure and thrust measurement. Combining with ~90% c* efficiency, a prototype thruster with 94% nozzle efficiency should be able to deliver 210-220sec vacuum Isp.

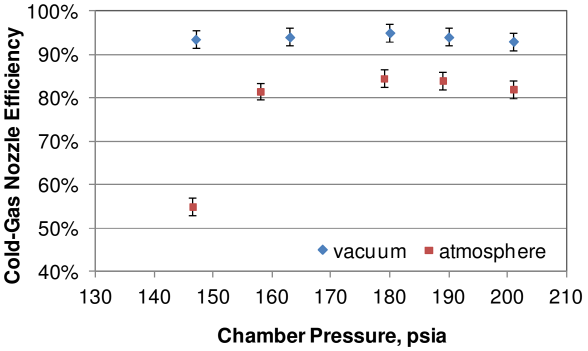

Figure 7: Nozzle Efficiency Measurement in Both Vacuum and Atmosphere Using Nitrogen Cold Gas

PIEZO-ACTUATED MICROVALVE

Busek's 0.5N AF-M315E thruster is coupled to a piezo-actuated propellant valve, shown previously in Figure 2. This piezo valve is a true "microvalve" in the sense that it weighs a mere 67g and consumes less than 0.5W of power. In comparison, state-of-the-art solenoid valves of similar flow level would weigh more than 100g while requiring 10-15W to operate. The infusion of a piezo microvalve makes the Busek thruster an especially attractive option for NanoSats that typically have strict mass and power budgets.

History of Busek's Piezo Microvalve

For more than ten years, Busek has been developing innovative, low-power, high-performance piezo microvalves for its electric propulsion thrusters, culminating in the delivery of flight-qualified hardware (Figure 8).[8] The major advantage of the piezo valves is their low power consumption (<0.5W) compared to state-of-the-art, space-qualified solenoid valves (which require several Watts or more). The extremely low power draw is particularly attractive on small spacecraft characterized often by tight power and thermal budgets. Piezo valves also offer high force capability, fast response, and precise controllability. These valves, however, are typically limited to low-flow applications due to the small displacement of their actuators (usually 0.1% of overall length, or tens of microns).

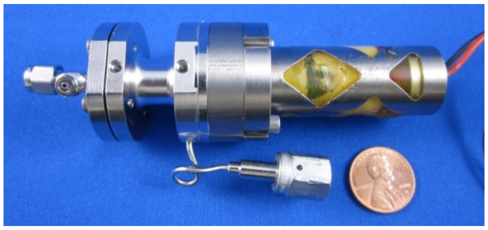

Figure 8: Busek's Flight-Qualified Piezo Microvalve Developed for NASA ST7 Colloid Thrusters

Microvalve for Green Monopropellant Application

Although piezo microvalves have many great attributes, designing one for chemical propulsion application is a rather challenging task. The main difficulty involves scaling up flow throughput given a very limited actuator displacement. In addition, typical chemical thrusters operate at a few hundred psi combustion chamber pressure, which adds stress to the internal mechanism of a thruster valve.

In an effort to find a suitable valve for its 0.5N AF-M315E thruster, Busek developed a revolutionary piezo microvalve that is low power, high pressure and most importantly, material compatible.[9] The valve, shown in Figure 9, features an all-welded design without any elastomer seal. Since very few materials are known to be long-term compatible with AF-M315E, all wetted surface of the valve is made of titanium, the only material proven inert to the propellant.

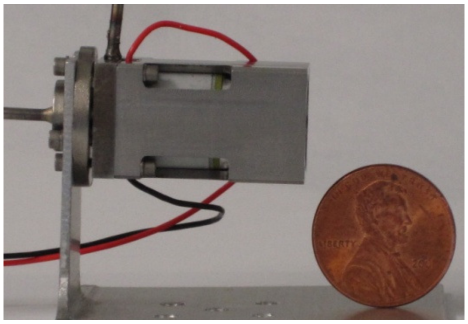

Figure 9: Busek's Phase-I Piezo Microvalve for Green Monopropellant Applications

The success of the Phase-I green monopropellant microvalve prompted a redesign that aimed to correct a few manufacturing issues. The developed Phase-II valve is shown in Figure 10. This updated valve design eliminates precision-machined parts and complex assembly procedures, which in turn improves reliability, repeatability and cost-effectiveness.

Figure 11 shows the flow capability of the Phase-II valve with the use of nitrogen gas. The observed hysteresis is common and can be eliminated with a closed-loop control, though it would not be an issue if the valve is used only for open/close. The valve is able to properly seal at 50psid while closed, and flow ~550sccm of N_2 gas when fully opened. The maximum flow rate corresponds to about 16mL/min of liquid water under the same differential pressure. For reference, the desired propellant flow rate is about 8.5-9.5mL/min, depending on the actual Isp delivered by the 0.5N thruster. The Phase-II valve is currently the default hardware for the 0.5N thruster. It will be subjected to environmental qualification upon the end of its development period.

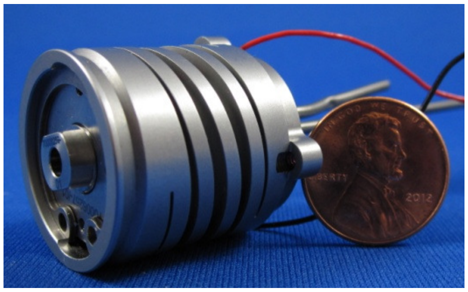

Figure 10: Busek's Phase-II Piezo Microvalve for Green Monopropellant Applications

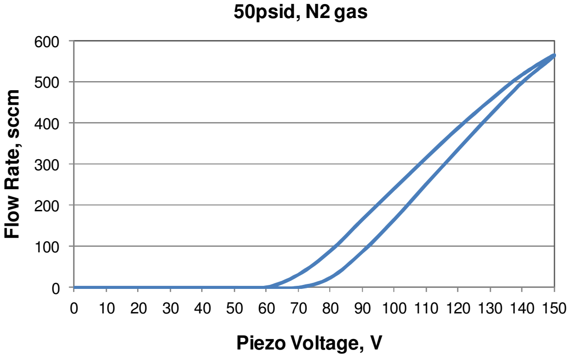

Figure 11: Gaseous Flow Curve of Busek's Phase-II Green Monopropellant Microvalve

CONCLUSION

The development status of Busek's 0.5N AF-M315E green monopropellant is discussed. In addition to achieving consistently high combustion efficiency, the thruster has demonstrated the ability to suppress catalyst-related degradation problems via a revolutionary reactor design. Combined with a high-performance micro nozzle, the 0.5N thruster is expected to deliver up to 220sec vacuum Isp.

The Busek thruster is complemented by a low-power, material-compatible piezo microvalve. The microvalve has genesis in Busek's previous flight-qualified hardware and is expected to pass qualification of its own. It is superior to state-of-the-art solenoid valves in terms of physical dimension, mass and power consumption. Benefitting from the use of the piezo microvalve, Busek's 0.5N AF-M315E thruster is a viable propulsion option for spacecraft as small as a NanoSat.

Future work on the thruster development includes full performance mapping, cycle-test for demonstrating minimum impulse bit and environmental qualification. The program is scheduled to conclude in the beginning of 2014. Flight opportunities are currently being pursued. Life-time and propellant throughput tests will be conducted based on individual mission requirements.

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