Testing Additively Manufactured Monopropellant Engine for Deep Space 6U CubeSat Applications

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The Students for the Exploration and Development of Space at the University of California, San Diego (SEDS@UCSD) Chapter is researching additively manufactured propulsion thrusters. Presented in this report is the first monopropellant engine, named Callan, designed and tested by SEDS@UCSD. This engine includes an additively manufactured diffuser section, reaction chamber, and nozzle module, which are printed in separate pieces to be bolted together. The catalyst pack is not additively manufactured and is assembled through traditional manufacturing processes. Presented in this document is the ground testing of Callan engine in Purdue University prior to Ground Tournament 3. The 3D printed thruster aims to promote the Cube Quest Challenge and its mission of completing a lunar orbit in December 2018.

I. Introduction

Designs for conventionally larger satellites have necessarily demanded, on average, \$10-100 million to fabricate. In lieu of their increasing costs and scales of development, CubeSats have generated much attention by NASA. CubeSats, by contrast to their conventional, larger satellite counterparts, exhibit an extraordinary advantage over space exploration due to its significant reduction in mass, power, development time and cost. Specifically, NASA has declared a second Centennial Cube Quest Challenge in order to expand research of these nanosatellites, and different approaches must be considered in order to maintain the highest caliber of efficiency. Students for the Exploration and Development of Space at the University of California, San Diego (SEDS UCSD) will be approaching this challenge by designing Triteia: a 6U configuration CubeSat designed to achieve a polar lunar orbit from a trans-lunar injection trajectory through the SLS EM-1 secondary payload deployment sequence. Triteia transforms from an unassuming, ordinary CubeSat to, instead, an autonomously intelligent power management system with a state-of-the-art additively manufactured high test hydrogen peroxide (H_2O_2) propulsion unit. This is an unprecedented level of detail in design as Triteia's propulsion system utilizes a high test H_2O_2 thruster, which allows for extraordinarily faster in-space translational speeds, and it includes direct metal laser sintering (DMLS) techniques that manufacture the thruster as 3 separate modules: the diffuser plate, reaction chamber, and the nozzle, thereby allowing for unlimited customization and total, aesthetic control. SEDS UCSD has embarked on designing an entirely new, Hydrogen Peroxide (H_2O_2) monopropellant propulsion system with never-before seen Delta-V and thrust capabilities onto the 6U Triteia CubeSat. Upon anticipation for securing the Lunar Derby prize in NASA's Cube Quest Competition, this sophisticated propellant structure will be one of the pioneers of its kind to evolve away from the conventional electric propulsion thrusters.

As monopropellant engines comprise mainly of a decomposition chamber, the capability of additive manufacturing techniques enables the designer to not only print the chamber, but additional interchangeable diffuser plates and nozzles placed on either side of the engine, in order to optimize the testing of reaction and expansion of the propellants. Doing so will rapidly reduce the time to develop the most efficient thrust design for an already limited, low thrust propulsion system. The main advantages of utilizing the additive manufacturing process are to allow for optimal design efficiencies, decreasing the production lead time and time interval between testing, in order to develop a flight-ready, small spacecraft thruster. This will further drive down the production costs and enable rapid prototyping for the variety of mission applications of the growing CubeSat industry.

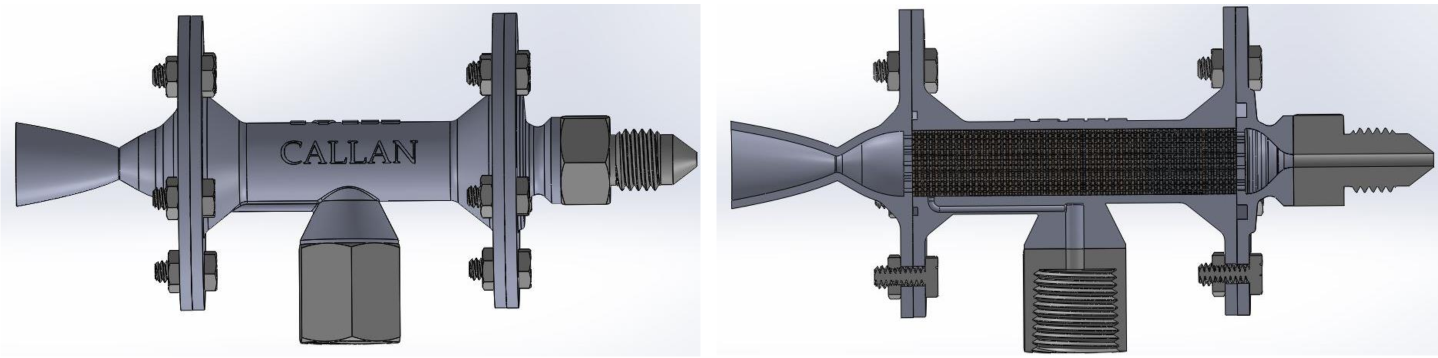


Figure 1: A computer generated model of the monopropellant engine, Callan: (a) Exterior view, (b) Interior cross-sectional view.

II. Test Configuration

The Callan thruster tests took place at Purdue University with Professor Timothee Pourpoint and his graduate student team from June 14th- 22nd of 2016. The objective of the testing was to obtain data about the thruster's pressure, temperature, thrust, heat flux across the thruster walls, and flow velocity of the propellant through the lines. Confirming the thruster design and efficiency from the thrust values at ideal steady state operation would then prove the flight technology readiness level of additively manufactured thrusters. The ideal testing of the Callan thruster was to perform a series of burn sequences or pulse tests and determine what amount of mass flow rate sprayed at the catalyst pack and at what time intervals would produce the highest temperature increase in the catalyst pack for the least amount of propellant. As a result, several pulse tests would be performed in order to compare which pulse length and at what interval would be the most efficient. After confirming the most efficient pulse, the thruster would then be tested at 15 sec and at 82 sec in order to replicate the burn times that have been calculated during mission operation. These steady state tests would help SEDS@UCSD analyze the fatigue and thermal stresses experienced by the thruster during long operation. The test matrix is shown below.

Figure 2: Callan Engine Purdue Test Matrix

Test Objective	Time Duration
Perform Pulse Test of Thruster	200 milli-sec
Perform Pulse Test of Thruster	400 milli-sec
Perform Pulse Test of Thruster	600 milli-sec
Perform Pressure-fed Test of Thruster	15 sec
Perform Pressure-fed Test of Thruster	82 sec
Simulate Blowdown-fed Test of Thruster	20 sec
Simulate Blowdown-fed Test of Thruster	20 sec
Simulate Blowdown-fed Test of Thruster	20 sec
Simulate Blowdown-fed Test of Thruster	20 sec
Simulate Blowdown-fed Test of Thruster	20 sec

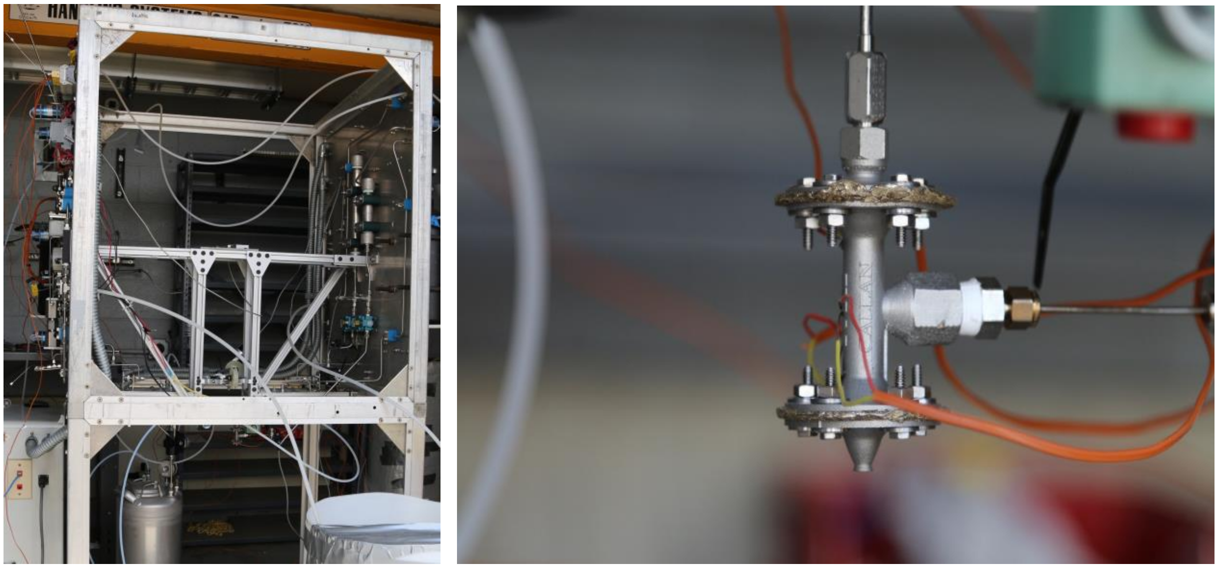


Figure 3: Callan Engine Setup at Purdue University June 17th, 2016

III. Theoretical Results

The purpose of pulsing the Callan thruster is to warm and prime the catalyst pack for sustained operation. As a result, the most important data for the pulse tests would be the temperature data at various locations on both the inside and outside walls of the thruster. The locations deemed the most critical were the top of the chamber, the mid section of the chamber, and the bottom of the chamber. Based on academic literature regarding hot fire tests and monopropellant hydrogen peroxide thrusters, the correct sequence to prime a thruster similar in size to the Callan thruster would have pulse lengths ranging from 200-600 milliseconds with 5 second intervals between each pulse and repeating this process 6 times for every pulse. Despite this research, the required number and length of pulses to successfully prime the thruster was suggested to SEDS@UCSD by Purdue personnel to be specific to every engine and every test conducted on any given day. As a result, the pulse tests conducted at Purdue University were conducted by tracking the data from the thermocouple located at the aft diffuser plate. After the first pulse test, the real time graphs from the thermocouple would rise exponentially, then approach a peak value and finally decrease. Once the graph would begin decreasing, another pulse was conducted and the graph would again rise but now reach a higher peak than before. The pulse lengths were instead ½ second pulses. This process was followed for all 3 pulse tests conducted at Purdue.

Based on the research of other hydrogen peroxide monopropellant rocket engines, it was expected that the temperature profile across the catalyst pack would increase as the distance from the front diffuser increased. That is, the temperature of the catalyst pack immediately following the front diffuser plate was expected to exhibit the lowest temperature. The maximum temperature of the catalyst pack would exist in the section just upstream of the aft diffuser plate. This temperature profile would exist during the transient stage of thruster operation. Once the thruster reached steady state from the priming of the catalyst pack, the catalyst pack would reach a uniform temperature profile across the catalyst pack at the decomposition temperature of 90% hydrogen peroxide at approximately 1400F or 1033K.

IV. Experimental Results

The experimental results for all three pulse tests conducted show a different temperature profile for the catalyst pack than was expected. Whereas the literature explains the highest temperatures to be at the aft diffuser plate, the tests showed the highest temperatures to be in the mid section of the two diffuser plates, followed by slightly lower temperatures at the front diffuser plate, and finally the lowest temperatures at the aft diffuser plate. This temperature profile was found true for all three pulse tests. Although this temperature profile was not expected, this data was confirmed by the infrared images and videos taken for each pulse test. Both pieces of equipment measured the maximum temperatures at the mid section for all three pulse tests.

Pulse Test 1

In terms of the maximum temperature of the thruster as a whole, it was determined that a temperature of 1400 F was reached on the inside of the decomposition chamber for the first pulse test. This is in agreement with the analysis, where the maximum expected operating temperature was found to be 1019.33 K or 1375.12 F. Although no thermocouples were used to directly measure the varying catalyst pack temperatures, this temperature for the first pulse test was confirmed by the high speed footage. The high speed footage shows there was a clear exhaust exiting the truncated nozzle. Because hydrogen peroxide decomposes into water and oxygen when in contact with a reactive catalyst, then a clear exhaust indicated that superheated steam (which is transparent) and oxygen (which is also transparent) was exiting the nozzle. As a result, these visual cues were a strong indication that full decomposition was taking place inside the thruster, as the images show:

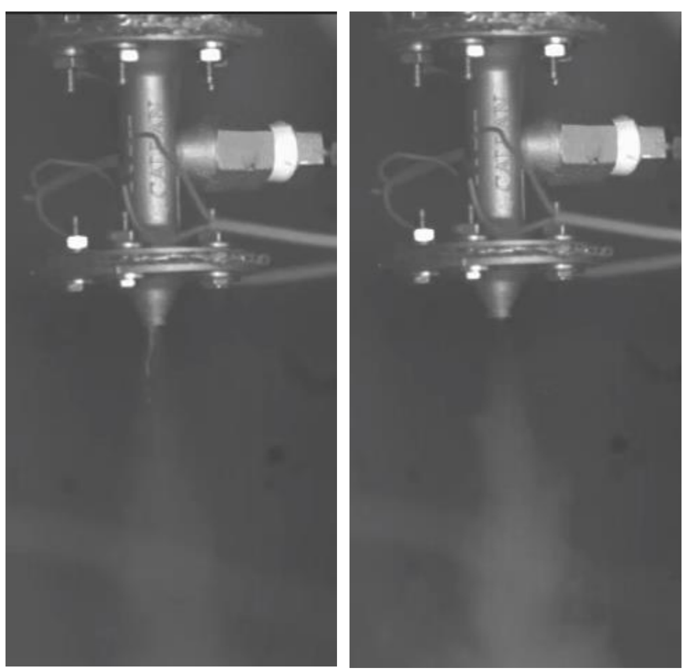
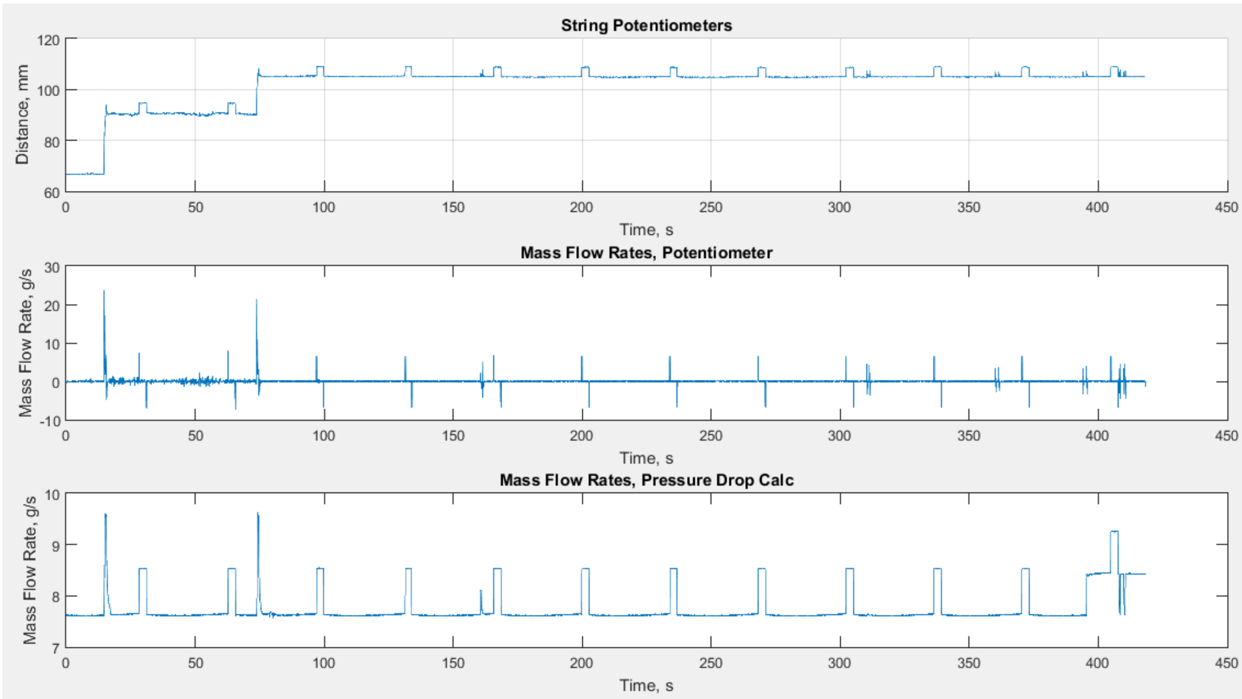
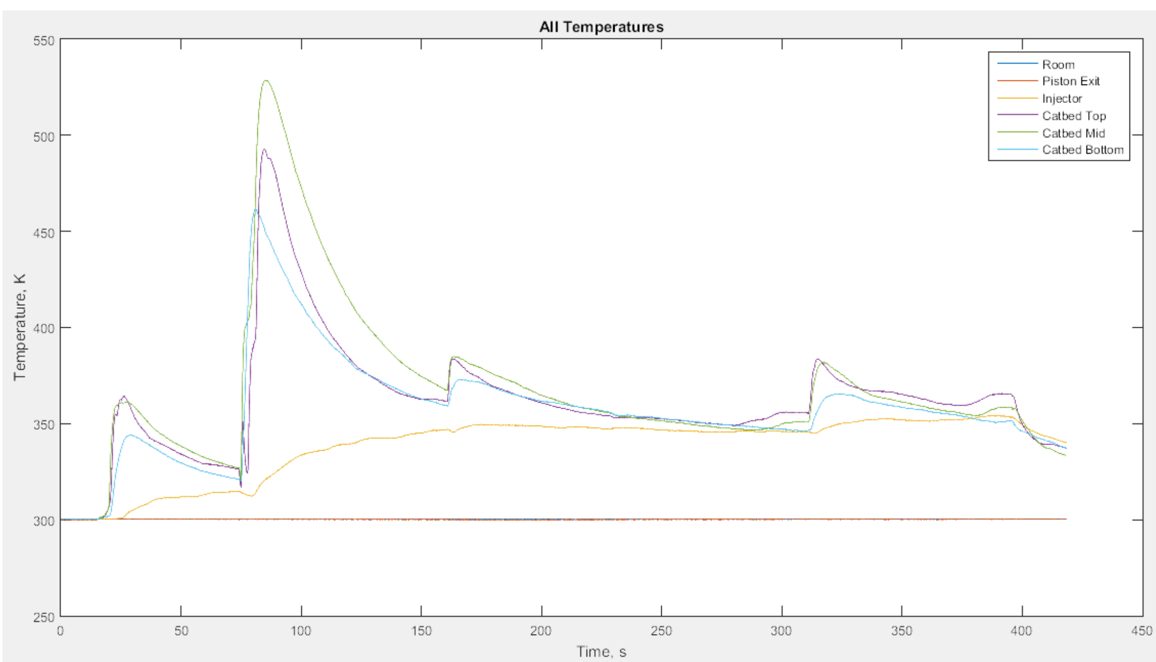


Figure 4: (Left to Right): Beginning and End of ½ Second Pulse Test

The heat generated from the decomposition process of the hydrogen peroxide was transferred through the decomposition chamber walls. The resulting temperature of the outer walls reached a peak of nearly 530 K or 495 F, as the thermocouple data shows below. This lower temperature on the outer wall is expected as Inconel 718 has a relatively low thermal conductivity of 22 W/mK.





Pulse Test 2

The second pulse test produced much different results than the first pulse test. The figures included below show that now, small droplets were exiting the truncated nozzle during the start of the pulse and a liquid stream was exiting the nozzle during the end of the pulse, unlike during the first pulse test.

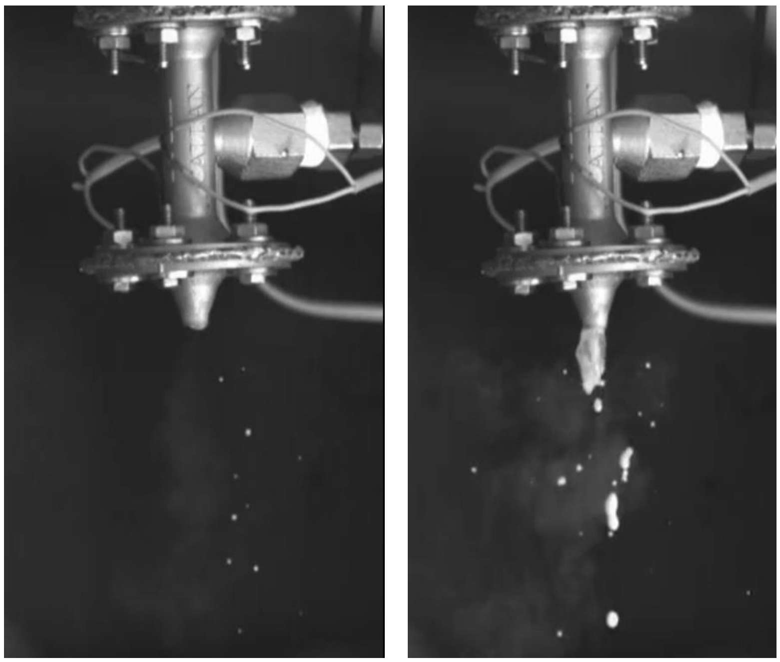
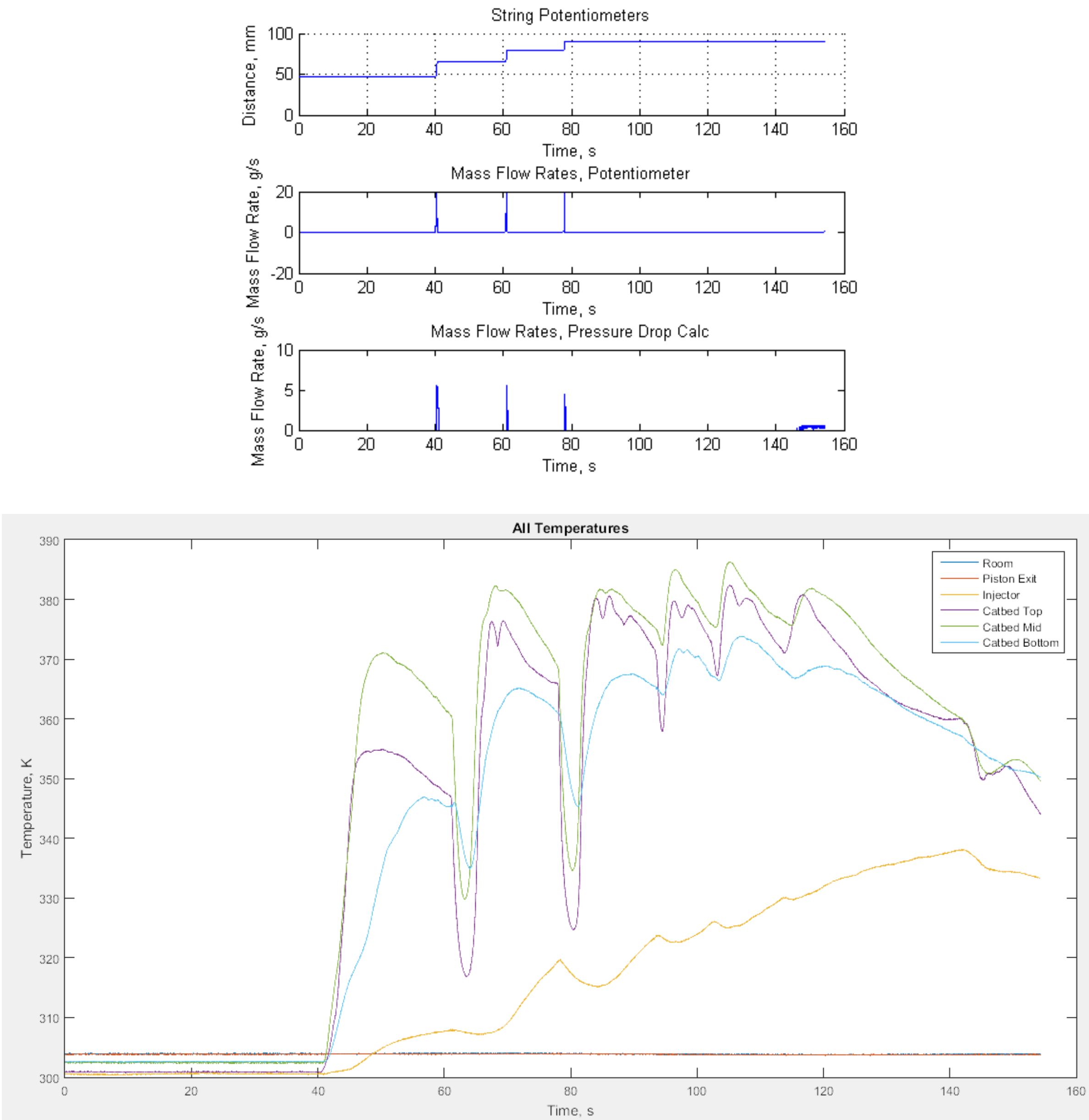


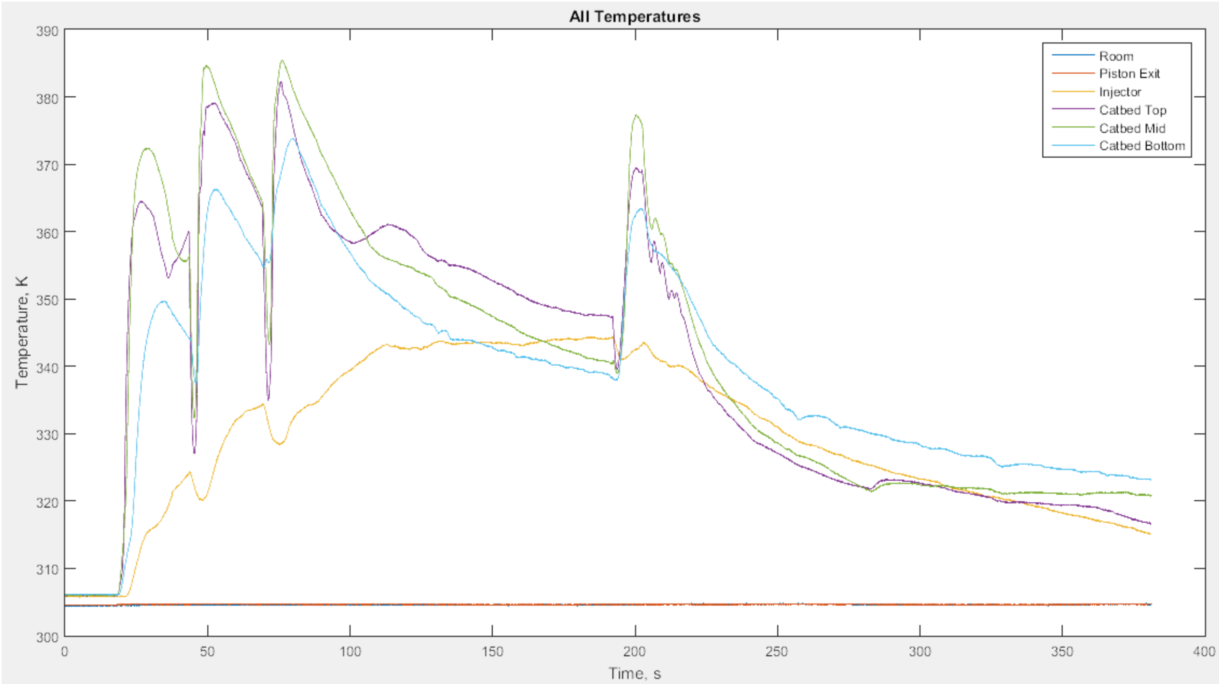
Figure 5: (Left to Right): Beginning and End of ½ Second Pulse Test

As the data shows, the string potentiometer, which shows the distance covered by the piston inside the tank, experienced much less resistance from the catalyst pack than it had during the first pulse test, as the distance between the steps is much closer. The mass flow rates are also a few grams less than those seen in the first pulse test and the temperature profile shows a much lower maximum temperature of 385 K as compared to the 530 K recorded during the first pulse test. Moreover, the temperature peaks from the first pulse test are not as stepped as those seen from the second pulse test.



Pulse Test 3

The third pulse test data differs from the second pulse test data in the same way the second pulse test data differs from the first pulse test data. The string potentiometer now showed an even smaller difference in the tank piston movement for each pulse length and as a result, produced even lower mass flow rates than before. The temperature profile between the second pulse test and the third pulse test however, is very similar. Since the temperatures were similar to those from the second pulse test, the images showing decomposition were exactly the same as those under the second pulse test. Droplets were exiting during the start of the pulse while a solid stream of 90% hydrogen peroxide was exiting towards the end of the pulse.


All Temperatures
Temperature, K
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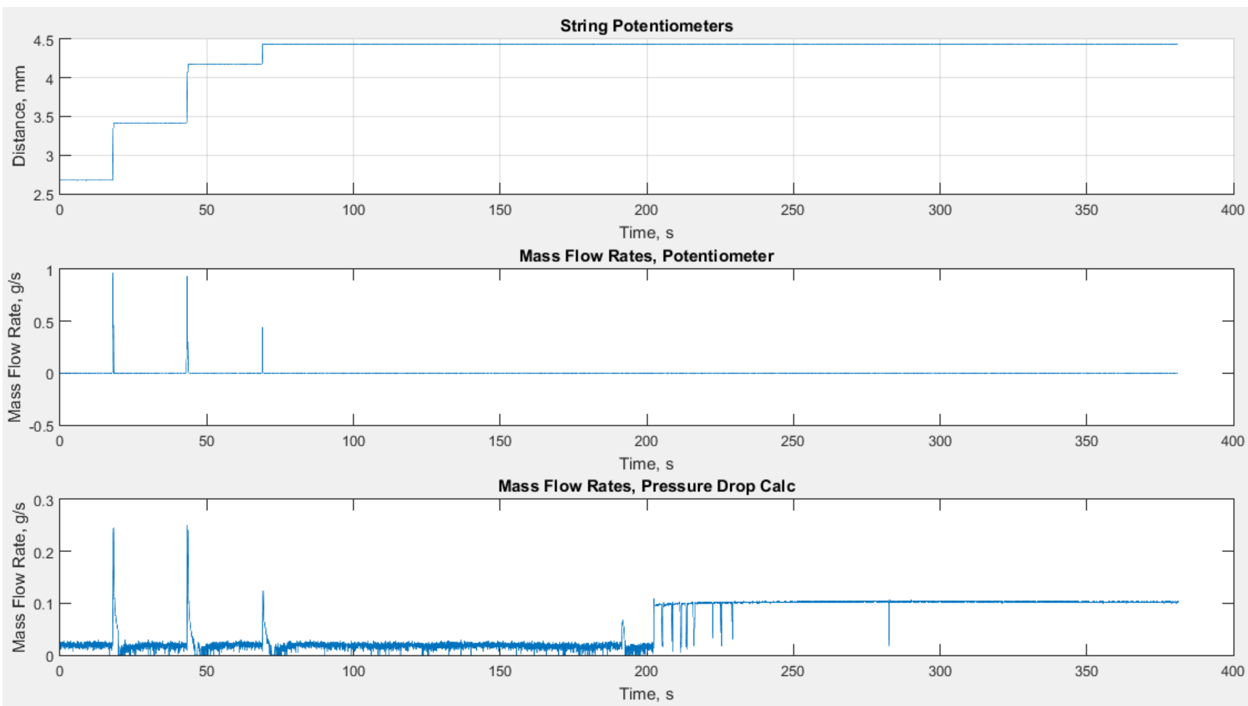
String Potentiometers
Distance, mm
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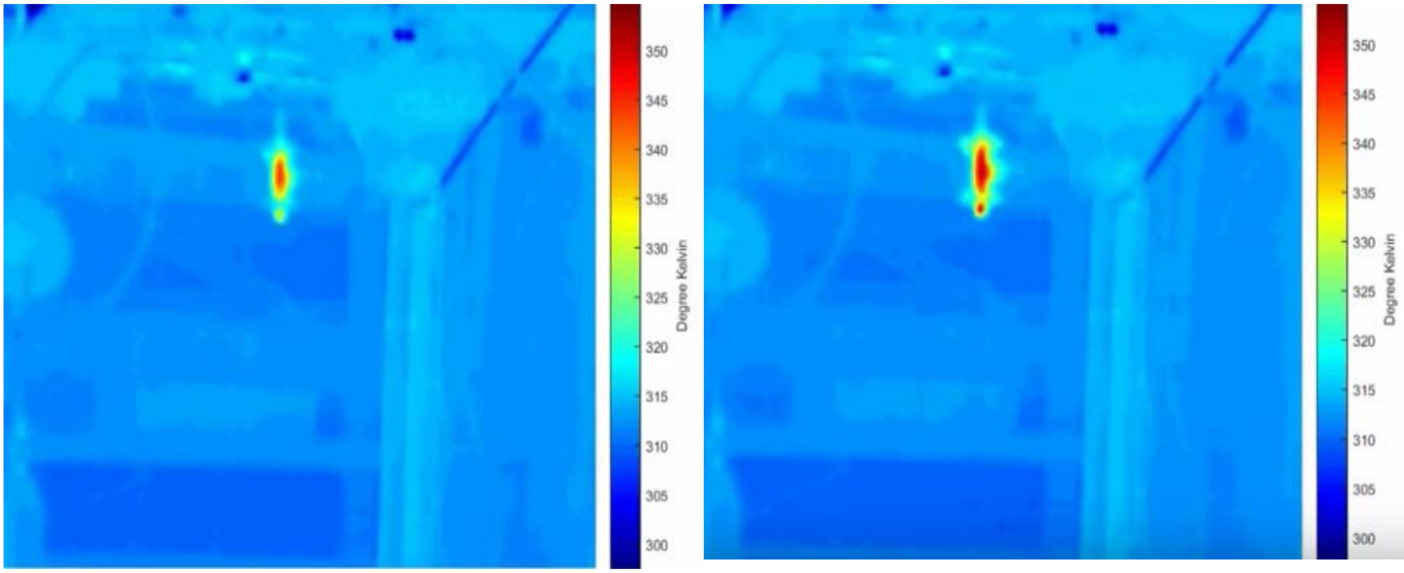

Figure 6: (Left to Right): Thermal Distribution during Pulse Test 3

V. Discussion

The second pulse test and the third pulse test showed incomplete decomposition of hydrogen peroxide through the catalyst pack. Due to the performance during the pulse tests, the steady state tests were never conducted and therefore data regarding thermal stresses and fatigue was never collected. After careful analysis, the differences between the three pulse tests were determined to be the result of a variety of reasons:

The first reason for the drastic loss in temperature and mass flow performance was due to a non-uniform diameter throughout the inside of the decomposition chamber where the catalyst pack was located. When the Callan thruster was received from MTI, it was discovered that the diameter of the metal printed chamber was smaller than the designated diameter of 0.32”. This was determined during the assembly of the catalyst pack where it was seen that the screens were slightly larger than the inner chamber diameter. Because of this, the chamber was reamed to a size of 0.32” before the thruster was sent to Purdue. When a 0.315” diameter pin with a known uniform diameter along its length was inserted into the decomposition chamber after the pulse test had been conducted, the pin had room to move around, indicating the nonuniformity in diameter of the decomposition chamber, as shown below:

Figure 7: Concentric Pin inserted into Decomposition Chamber

Due to the inaccurate machining process the Callan chamber became non concentric and created room for the Silver and Nickel catalyst screens to move around in the chamber. It was believed that after the initial pushback from the catalyst pack during the first pulse test, the catalyst pack screens no longer had a concentric seal with the inner diameter of the chamber. Instead, some screens were believed to have angled inside the chamber from the cracking pressure after the Purdue line valve opened. These loose screens then allowed an exit path for hydrogen peroxide, a path most likely through the gap between the chamber wall and the catalyst pack screens, causing poor decomposition and low reaction efficiency. Part of the reason the catalyst pack was able to move at all was because the catalyst pack could not be compressed with a hydraulic manual press. The intended compression of 2500 psi described in the literature was performed once and had deflected the orifice region of the front diffuser plate as shown below. As a result, the catalyst pack tested at the Purdue facility was packed without compression so that no further yielding would occur in the orifice region on the front diffuser plate. The poor decomposition and liquid flume exiting the truncated nozzle then can also be attributed to a non-compressed catalyst pack.

Figure 8: Deflected Orifice Region After ~1000 lb of Compressive Force

Figure 9: Disassembling the Catpack Screens

The Callan thruster catalyst pack also contained 2 Inconel 718 anti-channel baffles. The anti-channel baffles (ACBs) serve the monopropellant engine as placeholders for the catalyst pack but also help redirect the flow and prevent seeping of the propellant between the catalyst pack and the chamber wall. During the pack installment, the anti-baffle channel was first submerged into liquid nitrogen to contract then inserted into the chamber where it would then expand and provide the tight seal necessary to perform its function. However, the baffles only shrinked by a small amount of volume when the rings were taken out of the liquid nitrogen bath causing them to barely fit inside the chamber. There is a possibility that the baffles were poorly fitted during installment from the lack of baffle expansion inside the chamber. Another reason that may contribute to poorly fitted anti-channel baffles is the rough surface of the printed baffles. The rough surface potentially created space between the chamber wall and the baffle rim area and allowed hydrogen peroxide to pass through.

The deflected orifice region mentioned earlier caused uneven distribution of propellant flow through the front diffuser plate and also likely contributed to the poor decomposition results seen from the pulse tests. Due to the manner of deformation, the orifices that were designed to uniformly distribute propellant flow now directed all the propellant towards the center point of the catalyst pack. This lowered the efficiency of decomposition since only the inner region of the catalyst pack came in contact with hydrogen peroxide.

The final reason the pulse tests showed such poor decomposition and reaction efficiency was due to a compatibility issue between the gasket material and hydrogen peroxide. While it is stated in the McMaster gasket specification sheet that the gasket materials, vermiculite and stainless steel, would have excellent chemical compatibility with hydrogen peroxide and a high melting temperature, the gasket surrounding the entrance regions of the decomposition chamber wetted and dissolved into pulp and was carried through the catalyst pack because of the continuous flow of hydrogen peroxide. The gasket clogged the flow path of the propellant and minimized the contact surface between hydrogen peroxide and the catalyst pack, causing poor decomposition. As a result, the gasket material contaminated the catalyst pack, poisoned the silver screens and deactivated it as a catalyst.

Figure 10: Aft Diffuser Plate Post Firing Showing Wet Gasket (Left), Front Diffuser Plate Post Firing (Middle), Catalyst Screens with Gasket Residue (Right)

After the engine was printed using ProX 300 Printer by our sponsors at Metal Technologies (MTI), the structure was submitted to post-processing. This process began with removing the support medium from the engine using Wire EDM. Next, the measurements and dimensions of Callan were taken using a Zeiss CMM (coordinate measuring machine) to ensure that the geometry matched that of the initial design. The third and final step of post-processing polished the part using a laboratory polisher.

However,pictures included below show that a white fibrous material remained even after post processing. This caused the throat to be non-concentric and ultimately affected the expansion ratio of the nozzle and gave a performance much lower than was intended to provide. As the microscopic images show, the fibrous material was burned off but the throat diameter increased by almost a factor of two, as the dimensioning scale in the images shows.

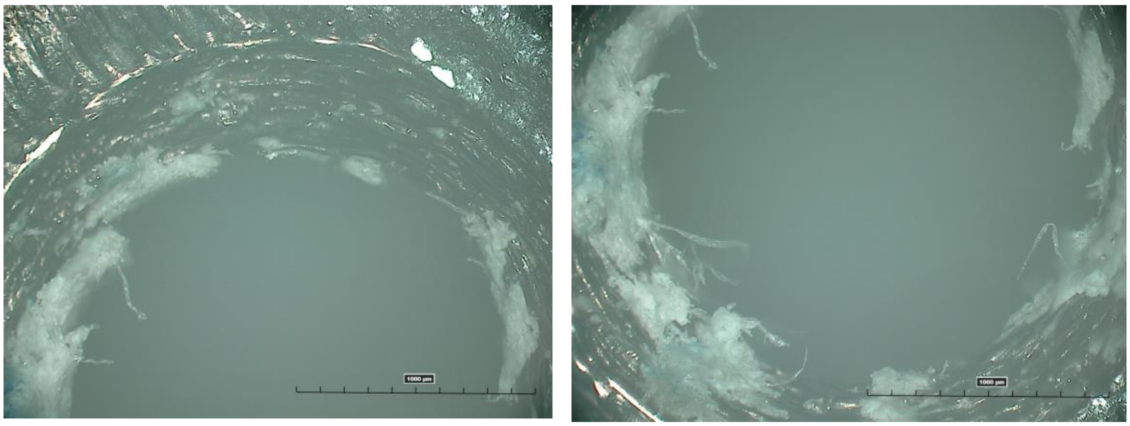

Figure 11: Non-concentric Throat Top (left),Bottom (right) Radius Before Pulse Tests

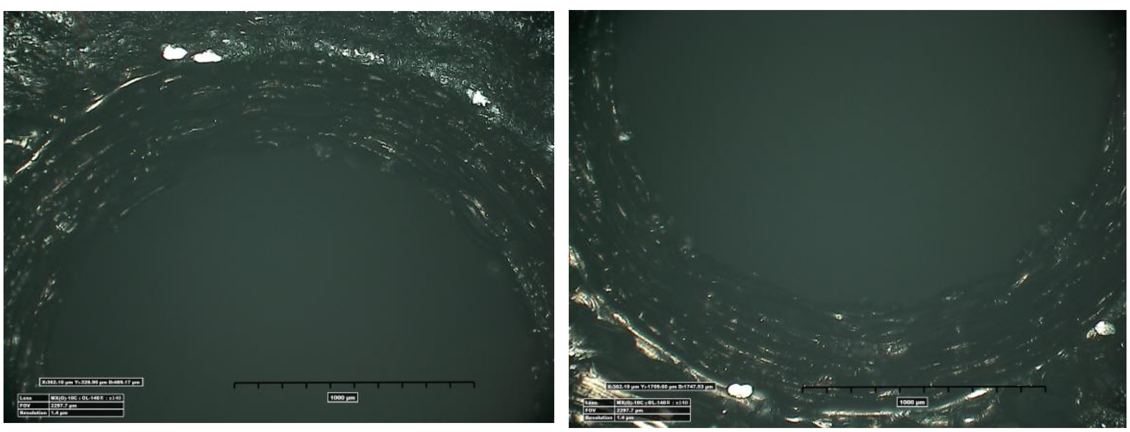

Figure 12: Non-concentric Throat Top (left), Bottom (right) Radius After Pulse Tests

The reasons mentioned above then explain the data behavior collected during the three pulse tests. The tendency of the piston tank to move in smaller increments after every pulse test was the result of the catalyst pack moving around. Initially, the piston tank had moved drastically from one location to another because the catalyst pack provided resistance towards the pressures the piston tank was pushing through the lines. The second and third pulse test string potentiometers showed less movement by the piston tank because the catalyst pack was no longer providing resistance. Instead, the pressure exited the tank much easier during the second and third pulse test, explaining the why the distance covered by the piston tank was much smaller. The result of less distance covered by the piston tank was smaller mass flow rates and a lower decomposition temperatures from the catalyst pack.

VI. Conclusion

The number of reasons for poor decomposition and reactive efficiency shows that a second design iteration of the Callan engine will be needed in order to improve its performance and determine its efficiency during steady state tests as well. The second design iteration will account for all the issues encountered above. The non-concentric chamber diameter will be accounted for by closely analyzing the shrinkage properties of the thruster material Inconel 718 during additive manufacturing so that the print becomes true to the design. Once the concentricity of the inner decomposition chamber is achieved, a greater emphasis will be placed on the post processing of the thruster. A smoother surface finish will be considered for the inside of the chamber in order to account for a tight seal between the contact surface of the screens, anti-channel baffles, and the inner decomposition chamber walls. The smooth surface finish will help ensure that the catalyst pack does not move around during the second design iteration. Unlike the gaskets chosen for the first iteration, metal C-rings will be considered for the second iteration in order to provide a better seal and increase the compatibility of the sealant with the propellant. Considering metal C-rings in place of vermiculite gaskets will prevent clogging and catalyst pack poisoning. These new design considerations will ensure that the second design iteration experiences full decomposition and reactive efficiency.

VII. Acknowledgments

The authors of this document would like to thank Dr. Timothee Pourpoint for taking his time and using his expertise to help us test Callan in Purdue Combustion facility. We would also like to thank Nick Nugent for logistical and theoretical support when designing this innovative engine. The engine design reached its final design before printing with the help of the Propulsion team, Ken Benedictos, Darren Charrier, Feennette Navarro and Daniel Lee. This project would not have been possible without the financial and logistical support from Jacobs School of Engineering, NASA Marshall Space Flight Center and MTI. We lastly would like to thank the Students for the Exploration and Development of Space organization at UC San Diego for supporting this project be a significant part of the group.