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PUMP FED HYDROGEN PEROXIDE ROCKET PROPULSION TESTING

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Rocket propulsion combustion research utilizing liquid propellants is typically performed using propellants supplied from pressurized tanks. Pressure-fed testing requires an onerous pressurization system, expensive high pressure tanks, and limited testing durations. A commercially available pump was identified as a candidate for supplying high pressure liquid propellants to small rocket thrusters. This high pressure positive displacement pump was utilized to supply rocket-grade 82% and 90% hydrogen peroxide to a monopropellant rocket thruster operated at chamber pressures up to 2,000 psi in a series of tests conducted at Purdue University. The pump was powered by an electric motor with a variable frequency drive for speed control. The operation of the pump and thruster system was examined experimentally at various pressure and mass flow rate conditions. Pump discharge pressure oscillations were measured and the response of the thruster to those oscillations is presented both with and without damping in the system. These tests successfully demonstrated that with careful characterization, a simple pump-fed system could be used to conduct rocket combustion experiments with significant operational flexibility.

I. INTRODUCTION

A high pressure positive displacement pump was used to supply rocket-grade hydrogen peroxide to a monopropellant rocket thruster or gas generator. The decomposition efficiency and chamber pressure stability of the gas generator in this system was observed at various operating conditions. The pressure oscillations imparted to the system by the pump were characterized by pumping water in both dampened and un-dampened hardware configurations. These same configurations were then hot-fire tested by pumping hydrogen peroxide at high pressure into the gas generator.

II. TEST EQUIPMENT DESCRIPTION

The tests were performed in the High Pressure Lab at Purdue University's Maurice J. Zucrow Laboratories. An aerial view of the lab is shown in Figure 1. The lab is situated adjacent to the Purdue University airport approximately one mile from the main campus. This remote location along with appropriately constructed facilities allow rocket propulsion, gas turbine combustion, turbo-machinery, energetic materials, and other noisy and hazardous testing to be conducted safely and productively. All testing activities were operated by remote control with video surveillance and capable data acquisition and control systems [1].

Figure 1. Aerial View of the Maurice J. Zucrow Laboratories at Purdue University

High Pressure Pump

The pump utilized for these tests was a high pressure diaphragm pump manufactured by Wanner Engineering, Inc. The pump, model Hydra-Cell D/G-15-X, is capable of flowing 10.3 gallons per minute at a maximum discharge pressure of 2,500 psi. The pump was driven by a 25 HP electric motor with a variable frequency drive for speed control. For the application of pumping high concentration hydrogen peroxide, Krytox® PFPE Oil with Soluble Additive was used as the hydraulic oil in the diaphragm pump. This oil was expected to minimize the risk of a catastrophic failure of the pump in the unlikely event

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a diaphragm would fail or leak that could expose hydrogen peroxide to the oil. An oil cooler, filter, and pump were installed to allow the diaphragm pump to operate at high pressure for extended run durations. All components of the pump that were wetted with hydrogen peroxide were passivated [3]. A detailed review of the pump design was also performed to be certain that hydrogen peroxide could not be trapped inside the pump where it could cause a pressure failure upon decomposition. A photo of the pump, coupled to the electric motor and oil cooler, is shown in Figure 2.

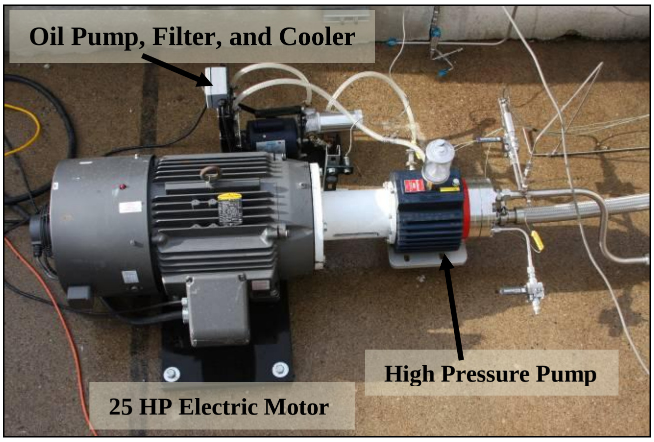

Figure 2. High Pressure Pump Installation

Hydrogen Peroxide Gas Generator

The H_2O_2 gas generator (GG) utilized for testing was manufactured by General Kinetics Inc., part number GK-PD039-201-003. This GG was tested previously at Purdue with H_2O_2 supplied from a pressurized tank. From a pressurized tank, the GG demonstrated 99% decomposition efficiency at all operating conditions with stable chamber pressures [2]. GG exit nozzles were manufactured with throats sized for the specific operating conditions of the pump tests. The GG as installed for testing is shown in Figure 3.

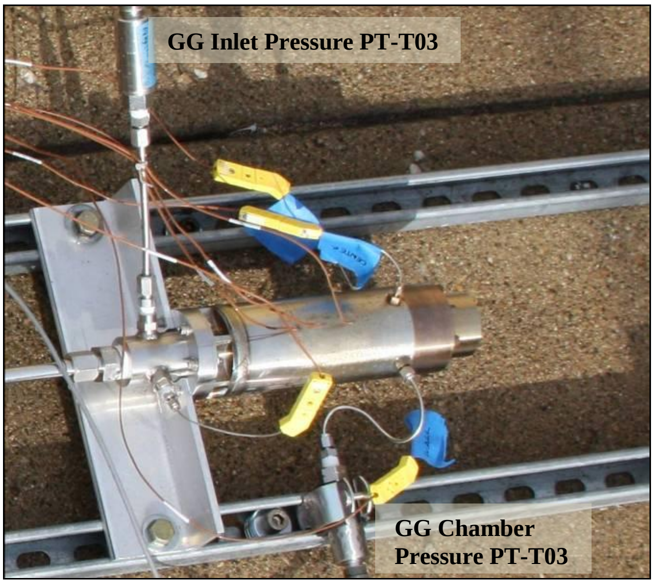

Figure 3. H_2O_2 Gas Generator with Temperature and Pressure Instrumentation Installed

Experimental Setup

A photograph of the over-all experimental setup is shown in Figure 4. An electro-polished 55 gallon 304

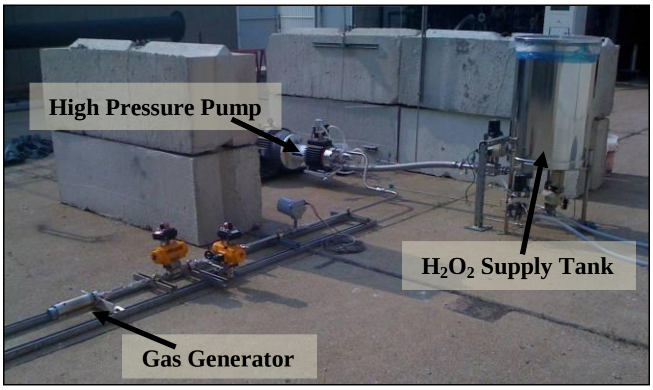

Figure 4. High Pressure Pump-Fed H_2O_2 Gas Generator Experimental Setup at Zucrow Labs

stainless steel barrel served as the source of H_2O_2 to the pump. The barrel was filled with H_2O_2 by test technicians manually transferring fluid via siphon pumps from the 30 gallon aluminum drums supplied by FMC Corp. Pneumatically actuated ball valves were used throughout the setup for remote control of the system. The valves allowed either H_2O_2 or DI water to be supplied to the pump and the tank to be flushed with DI water. Valves near the GG allowed DI water to be flushed through the system without putting it through the GG. Dry nitrogen gas was used for purging. A pressure relief valve (PRV), shown in figure 5, was also installed in the pump discharge line

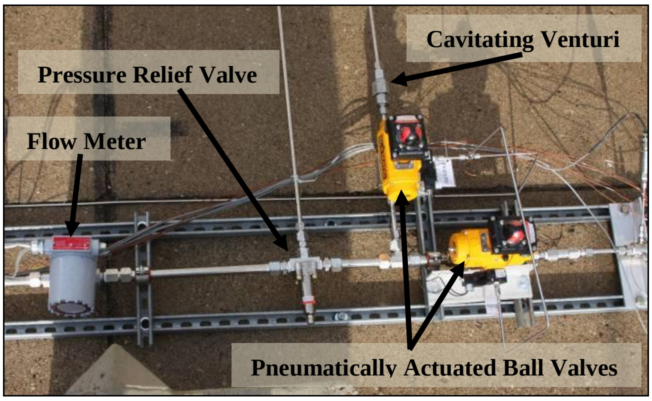

Figure 5. Flow Meter and Pressure Relief Valve Upstream of GG Isolation and Bypass Valves

to prevent dead-heading the pump. A cavitating venturi was installed in the dump flow circuit that allows the discharge of the pump to bypass the GG. The cavitating venturi created a back pressure on the pump allowing pump performance, including system pressure oscillations, to be measured.

A National Instruments LabVIEW control panel was created for operating the experiment remotely. A screen-shot of the user interface is shown in Figure 6.

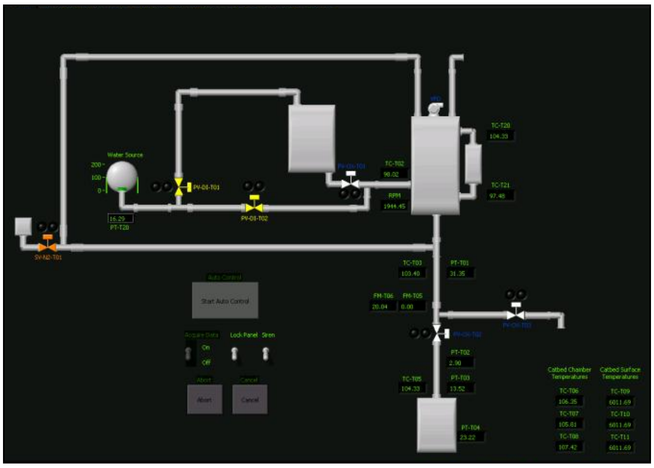

Figure 6. Control Panel for Pump Experiment

Table 1 lists the instrumentation installed for the pump experiments. 16 bit data was acquired at 1,000 samples/sec/channel on all instrumentation.

Table 1. H_2O_2 Pump / GG Instrumentation List

ID	Description
PT-T01	H_2O_2 Pump Discharge Pressure (psia)
PT-T02	Cavitating Venturi Inlet Pressure (psia)
PT-T03	Gas Generator H_2O_2 Inlet Pressure (psia)
PT-T04	Gas Generator Chamber Pressure (psia)
PT-T20	DI Water Supply Pressure (psia)
FM-T05	Flow Meter Volume Flow Rate (gpm)
FM-T06	Flow Meter Fluid Temperature (deg F)
RPM	Pump Tachometer (revolutns per minute)
TC-T01	H_2O_2 Barrel Fluid Temperature (deg F)
TC-T02	H_2O_2 Pump Inlet Temperature (deg F)
TC-T03	H_2O_2 Pump Discharge Temp (deg F)
TC-T05	GG H_2O_2 Inlet Temperature (deg F)
TC-T06	GG Chmbr Gas Temp Near Wall (deg F)
TC-T07	GG Chamber Gas Mid Location (deg F)
TC-T08	GG Chmbr Gas Temp Centerline (deg F)
TC-T09	GG External Temp Forward (deg F)
TC-T10	GG External Temperature Mid (deg F)
TC-T11	GG External Temperature Aft (deg F)
TC-T20	H_2O_2 Pump Oil Discharge Temp (deg F)
TC-T21	H_2O_2 Pump Oil Return Temp (deg F)

III. TEST RESULTS

Three series of pump-fed monopropellant GG tests were conducted from May through December 2011. The same pump, PRV, and GG were used for all tests. Prior to initiating testing, the propellant barrel would be filled with the DI water or the desired concentration of H_2O_2. Appropriate valves would be opened and the pump and propellant lines would be primed by operating the pump at low speed, flowing not through the GG, but through the valve leading to the dump container. The changes that were made to the test configuration for each test series are described with the presentation of test results.

Test Series I: Baseline Configuration - 90% H_2O_2 with GG, No Suppressor & No Cavitating Venturi

The Plumbing and Instrumentation Diagram (P&ID) for the Series I baseline test configuration is shown in Figure 7.

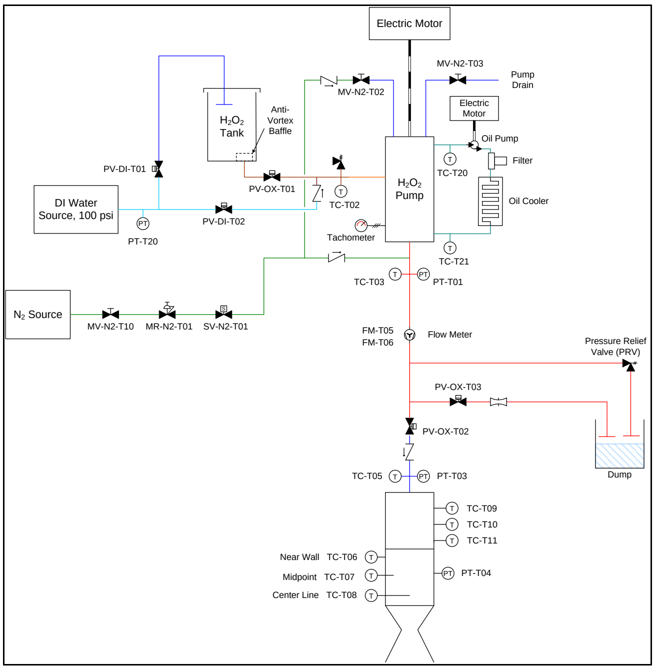

Figure 7. Test Series I: Baseline Configuration P&ID

The high pressure pump contains five Viton diaphragms that perform the actual pumping. With these small individual diaphragm displacements, the pump provides relatively small oscillations in the discharge pressure. The pump was tested with a cavitating venturi in use to provide back pressure to the pump. The discharge pressure is shown in Figure 8 at various operating speeds. Pump discharge roughness was less than 10% of the operating pressure at all tested conditions.

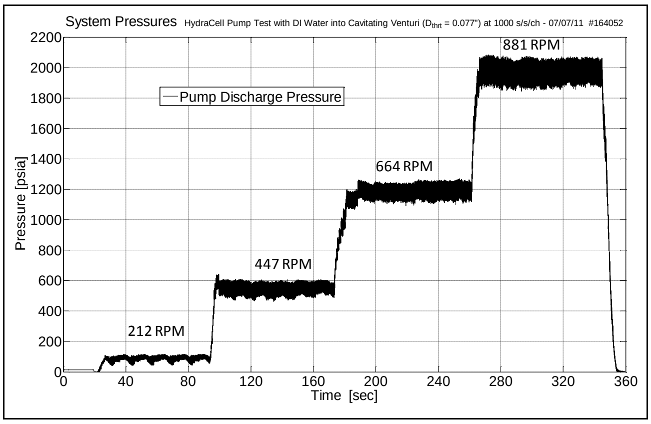

Figure 8. Pump Discharge Pressure with DI Water at Various Operating Speeds

The GG was tested with 90% H_2O_2 at the same pump operating conditions. The pressure oscillations at the discharge of the pump increased dramatically when coupled to the GG. These system pressures are displayed in Figure 9 at the various pump operating

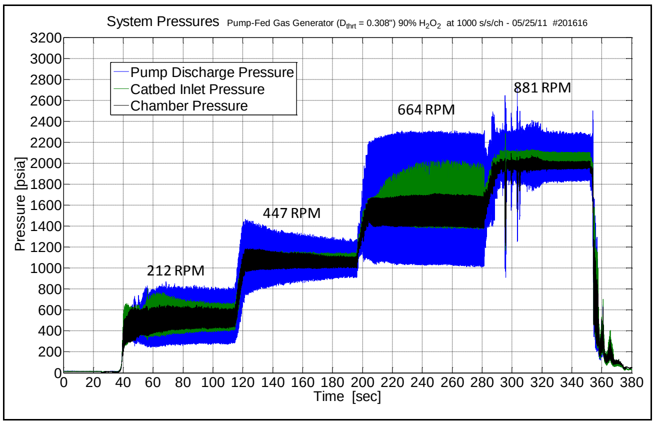

Figure 9. Baseline Pump/GG System Pressures at Various Operating Speeds with 90% H_2O_2

speeds. A fast-Fourier transform (FFT) was used at each operating speed to determine the dominant frequency components of the pump discharge pressure. As shown in Table 2, the FFT results matched very closely the expected driving oscillations from the pump rotating speed operating with five diaphragms.

Table 2. Pressure Pulses Excited by Pump

Test Pressure (psia)	RPM	Expected Pressure Pulses/sec	FFT Results (Hz)	% Diff
500	212	17.67	18.11	2.51
1000	447	37.25	37.88	1.69
1500	664	55.33	56.02	1.25
2000	881	73.42	74.25	1.14

In spite of the significant pressure oscillations, the GG performed admirably. Figures 10 displays the rise in H_2O_2 temperature as it passes through the pump as well as the increase in pump oil temperature.

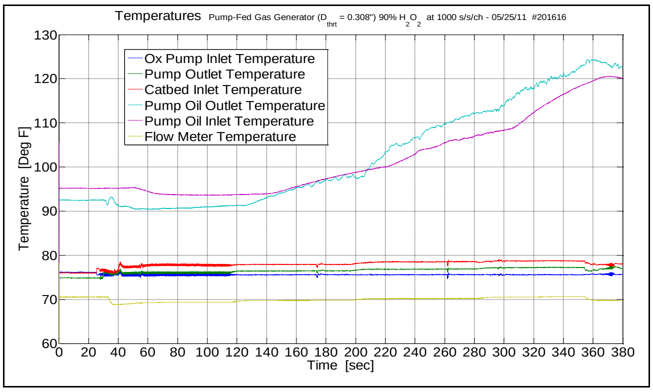

Figure 10. H_2O_2 Pump Operating Temperatures

The temperatures in Figure 11 show the GG is operating at 100% decomposition, or C*, efficiency. The thermal mass flow meter installed in the system did not provide meaningful data in these highly

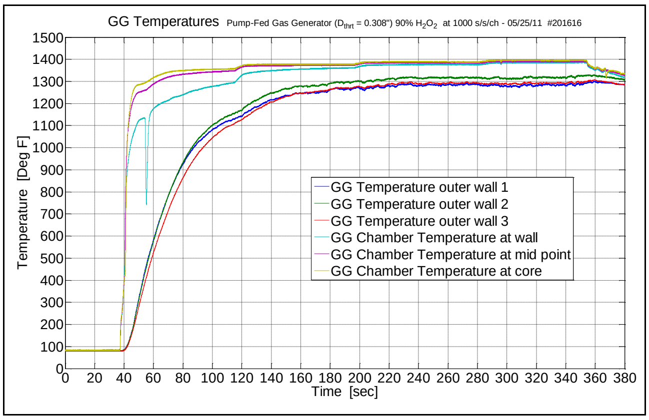

Figure 11. 90% H_2O_2 GG Operating Temperatures

oscillatory operating conditions. As such, the mass flow rate shown in Figure 12 was calculated using C* efficiency derived from the core chamber temperature of the GG.

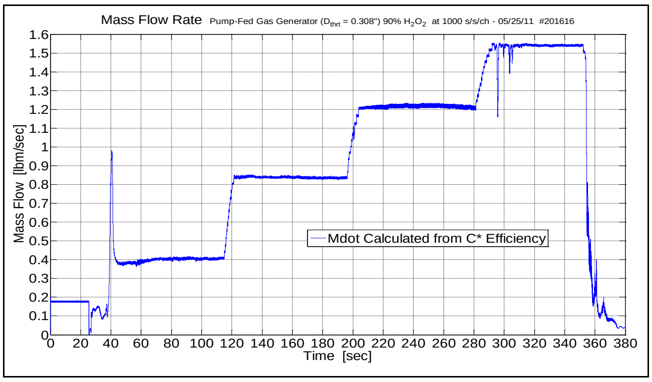

Figure 12. System H_2O_2 Mass Flow Rate

*Test Series II: 90% H_2O_2 with GG, **Addition** of a Pulsation Suppressor but No Cavitating Venturi*

The Plumbing and Instrumentation Diagram (P&ID) for the Series II test configuration with a pulsation suppressor is shown in Figure 14. The suppressor was procured from the Wilkes and McLean Company, Part Number: WM-3081-12SSVITW. A cross section of the suppressor is shown in Figure 13. It consists of a

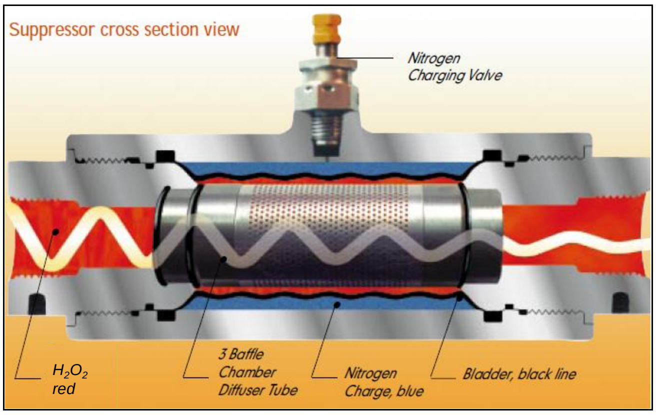

Figure 13. Hydraulic Fluid System Pulsation Suppressor

stainless steel outer pressure shell encompassing a cylindrical Viton liner. Within the Viton liner is a porous cylinder or diffuser tube. The space between the outer shell and the Viton liner was pressurized with

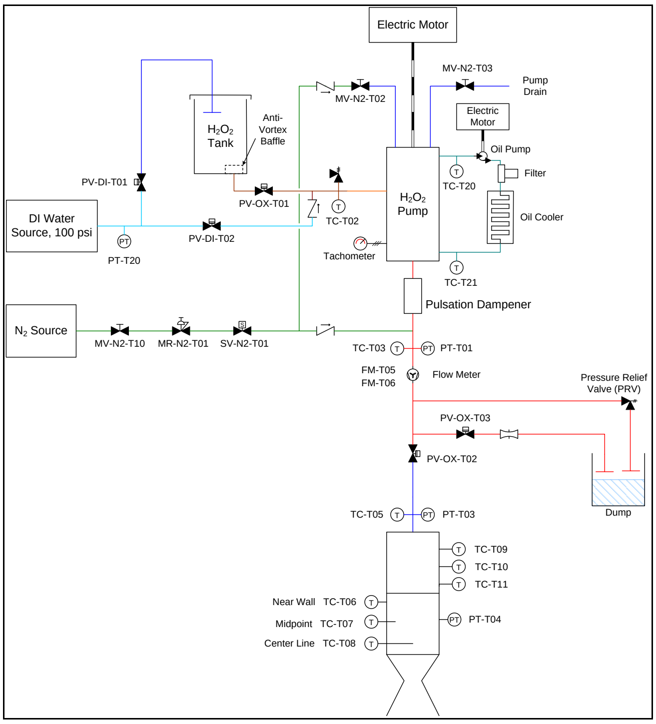

Figure 14. Test Series II: Pulsation Suppressor Configuration P&ID

nitrogen to 1,500 psi, adding a compressible gas volume to the incompressible fluid system. The recommended installation location is close-coupled to the source of the pressure pulses to be suppressed.

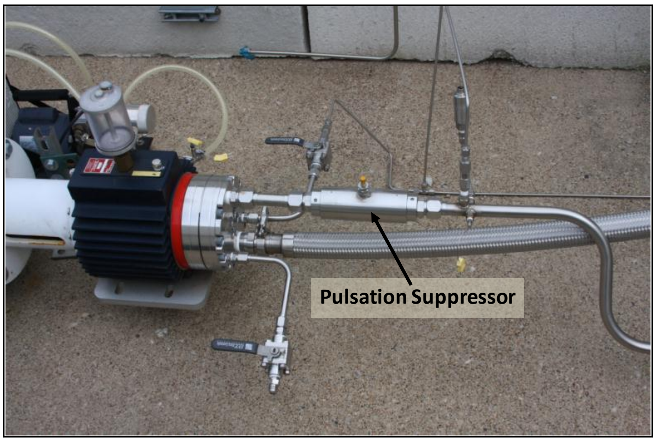

Figure 15. Pulsation Suppressor Installation Close-Coupled to H_2O_2 Pump

Unfortunately the suppressor increased the system pressure instability, as shown in Figure 16. This response to the decrease in propellant feed system "stiffness" confirmed that our system had a significant chug instability [4].

The GG continued to start and perform well as indicated by a clear plume and the chamber thermocouple measurements presented in Figure 17.

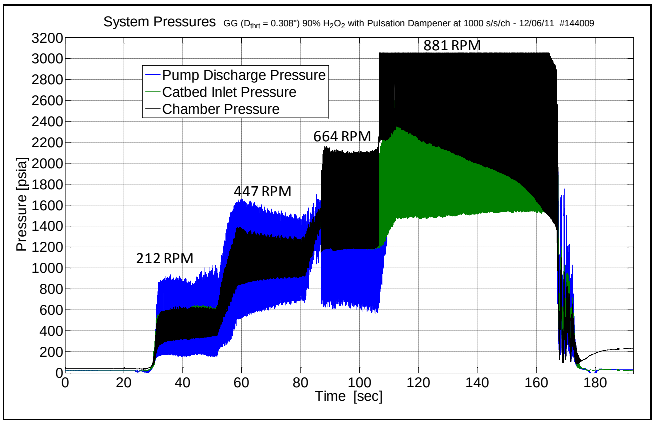

Figure 16. Suppressor Pump/GG System Pressure Response at Various Speeds with 90% H_2O_2

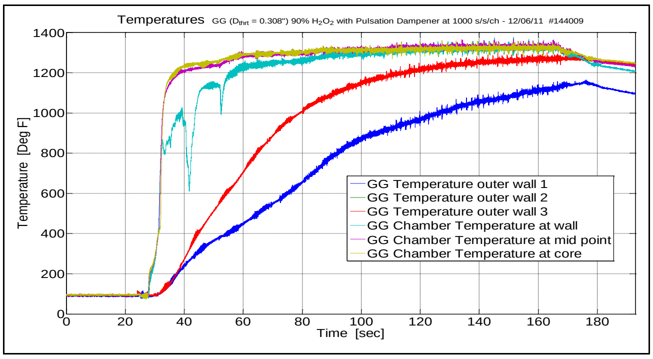

Figure 17. 90% H_2O_2 GG Operating Temperatures

Test Series III: 90% H_2O_2 with GG, Pulsation Suppressor, and ***Addition*** *of a Cavitating Venturi*

A cavitating venturi was added to the system just upstream of the GG as shown in Figure 18. The addition of a venturi requires additional system pressure budget to achieve the same mass flow rate throughput. Depending on the installation, however, cavitating venturis can achieve a total pressure recovery of approximately 85%.

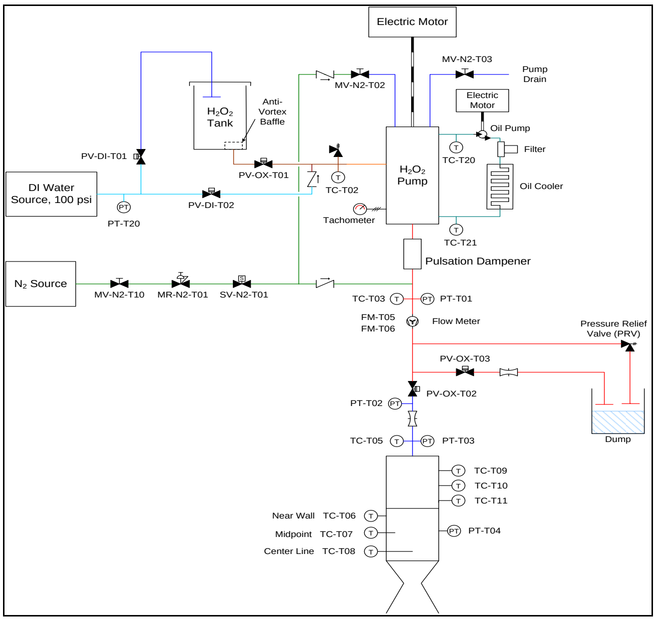

Figure 18. Test Series III: Pulsation Suppressor with Cavitating Venturi Configuration P&ID

As shown in Figure 19, the cavitating venturi decoupled the pressure oscillations from the pump and GG resulting in the desired stable system performance.

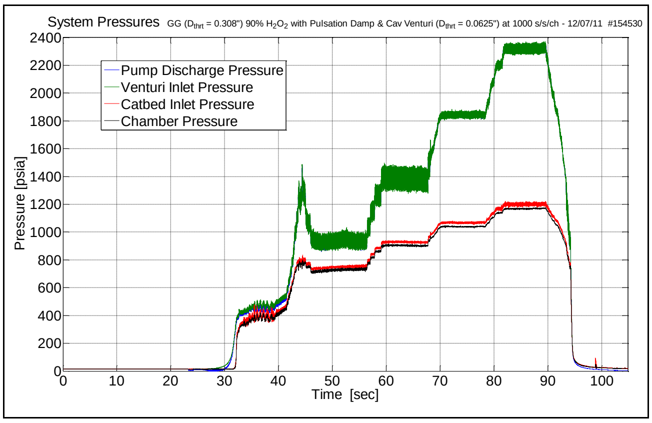

Figure 19. Suppressor & Cavitating Venturi Pump/GG System Pressure Response at Various Speeds with 90% H_2O_2

While the addition of this cavitating venturi reduced the system H_2O_2 mass flow rate, it facilitated a robust measurement. The diminished pressure oscillations also allowed the installed mass flow meter to provide a flow rate measurement. Both measurements are displayed in Figure 20. Note that prior to time 42 sec on Figure 19, there is not a 15% pressure drop between the venturi inlet and the GG inlet. This indicates that the venturi is likely not fully cavitating or not cavitating at all. Though not cavitating, the flow resistance through the venturi is adequate to provide stable operating conditions over the range of tested operating conditions.

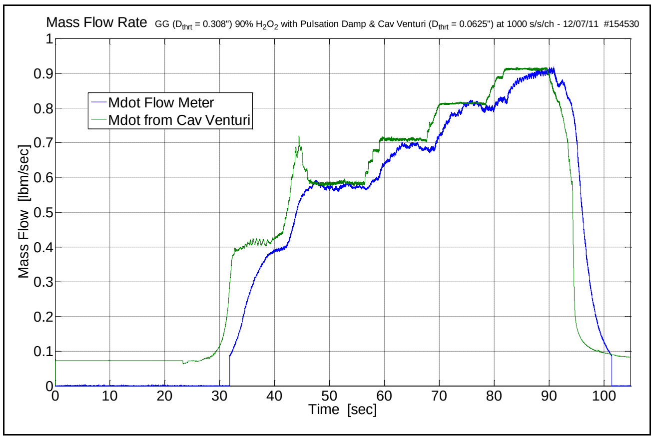

Figure 20. 90% H_2O_2 Mass Flow Rate

While the GG continued to produce a clear plume and near theoretical adiabatic exhaust gas temperatures, the valid mass flow rate measurements allowed the direct calculation of C* efficiency which is plotted in Figure 21. The GG catalyst bed pressure drop was consistent throughout all testing. The performance during this test with the cavitating venturi is shown in Figure 22.

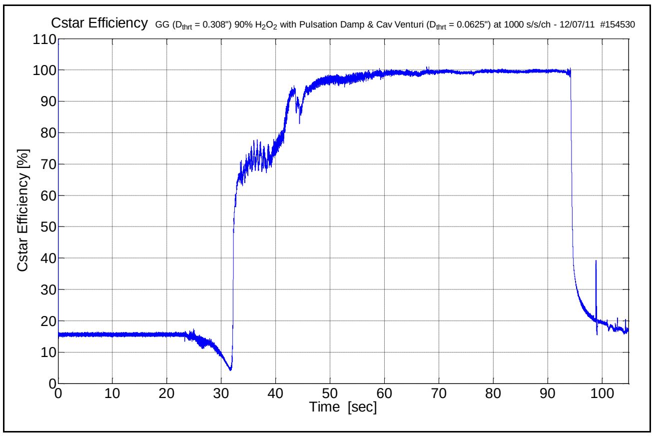

Figure 21. GG 90% H_2O_2 C* Efficiency

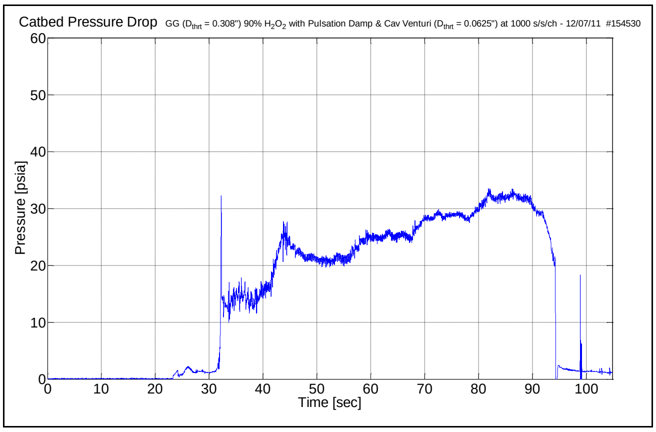

Figure 22. GG 90% H_2O_2 Pressure Drop

To investigate a rapid GG start transient using the high pressure pump, the pump was operated at the required speed to provide the desired H_2O_2 flow rate with a cavitating venturi installed. All flow from the pump was exiting the system through the pressure relief valve prior to opening the GG fire valve. Figure 23 shows the pump discharge pressure is approximately 2,800 psia prior to initiating flow to the GG.

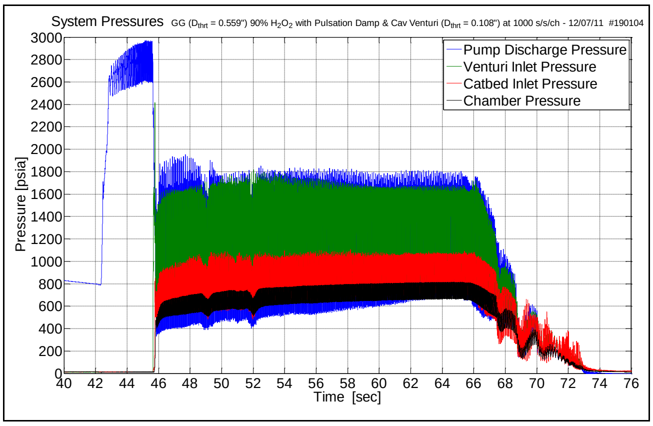

Figure 23. System Pressures During Slam Start of GG to Investigate Start Transient Operability

When the GG fire valve is opened 45.63 seconds, the venturi inlet pressure begins to rise. As the H_2O_2 begins flowing to the GG, the pump is no longer being back pressured by only the PRV and its discharge pressure falls below the cracking pressure of the PRV. Figure 24 presents the start transient performance of the pump-fed GG. This particular operating condition, in spite of having a cavitating venturi, experienced a chug instability.

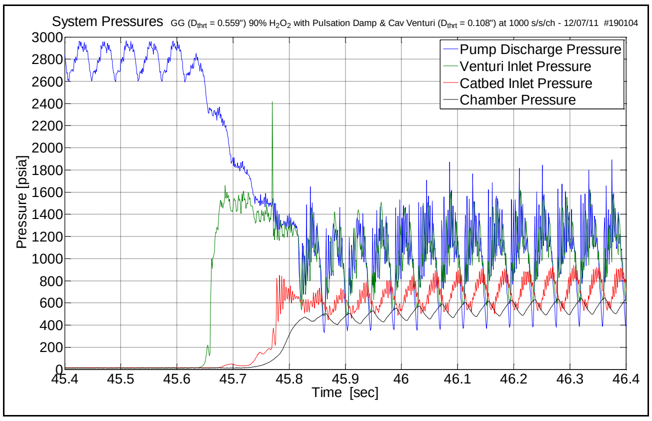

Figure 24. System Pressure During Start Transient

IV. CONCLUSIONS

A high pressure positive displacement pump was used successfully to supply rocket-grade hydrogen peroxide to a monopropellant gas generator. A system configuration was identified to produce stable high performance operation at a wide range of operating conditions. The dynamics imparted to the system by a pump add complexity that must be analyzed carefully to assure success.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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