Development and Characterization of a Closed-Loop Nitrous Throttling System for a Hybrid Rocket Lander

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Hybrid engines have been increasing in viability for lander-type rockets due to their operational safety and cost-effectiveness for commercial applications. Their ability to throttle thrust via oxidizer mass flow rate makes them well-suited to the continuous thrust adjustment landers require. Precise thrust control is typically accomplished through a closed-loop throttling system that continually regulates thrust relative to a real-time thrust profile, yet implementation challenges remain for certain propellant combinations. Propulsive Landers at Georgia Tech (hereafter GTPL) is developing a hybrid engine and corresponding oxidizer throttling system for a proof-of-concept lander intended for surface hop maneuvers. Nitrous oxide was selected as the oxidizer due to its nontoxic, storable, and self-pressurizing properties, but it also presents thermodynamic challenges. Operating near the vapor pressure of nitrous, the system is susceptible to rapid pressure drops, which induce two-phase flow instability and limit flow through the piping. This results in reduced usable liquid oxidizer and degraded throttling control authority. In order to minimize flashing and address resulting challenges, GTPL developed a servo-actuated, subcooled nitrous throttling valve operated by a closed-loop controller utilizing chamber pressure readings as feedback. The system was characterized and validated through a series of open and closed-loop coldflows and hotfires across a range of valve positions. System response was assessed through both steady-state and transient throttling to quantify effective throttling regimes and thrust limits. This paper details the development of the throttling mechanism, experimental results, and future improvements and design considerations for nitrous-based throttling systems.

I. Introduction

Hybrid engines are a much safer alternative to their liquid and solid counterparts, as they employ non-toxic oxidizers and can be operated and stored with minimal risk of detonation during handling [1]. They share the benefits of a simplistic solid rocket fuel grain as well as the throttling and restart capabilities that liquid engines possess. However, compared to liquid rockets, hybrids enable safer transport, storability, and reduced costs due to the simplicity and reusability of their design [2].

For the development of this engine, nitrous oxide (N_2O) was chosen as the oxidizer. Nitrous provides several advantages over other commonly used oxidizers, such as liquid oxygen (LOX) and hydrogen peroxide (H_2O_2). Nitrous is a non-toxic and non-flammable species, enabling safer handling. Additionally, nitrous is self-pressurizing, removing the need for additional pressurants and corresponding equipment. In order to achieve a self-pressurized state, the nitrous exists in a saturated condition, where both liquid and gaseous states exist at their equilibrium [3].

Most fuel throttling systems restrict the flow of propellant by way of a valving mechanism and can be controlled either with an open-loop or closed-loop controller [4]. Open-loop throttling defines any method where all instructions provided to the controller, and therefore the thrust profile, are predefined before flight. Closed-loop throttling, the system of choice for this paper, sends real-time feedback from a given sensor or measured parameter to a controller that adjusts the valve as needed. Closed-loop throttling is the most prevalent system within the industry, given the necessity for precise momentary adjustments and factors such as nozzle erosion and fuel grain regression that influence relations the controller relies on [5].

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Using nitrous presents a set of thermodynamic challenges that must be accounted for to throttle effectively. As the system operates near the vapor pressure of nitrous, components that the oxidizer passes through cause rapid pressure drops [6]. This induces instabilities in the flow and can lead to flashing, or rapid boiling, of the species. Flashing results in damage through the valves and pipes and restricts flow rate, often leading to conditions similar to choked flow. This inhibits the control authority of throttling systems and renders large portions of the oxidizer supply unusable.

This paper details the development of the throttling system at both a hardware and software level, as well as considerations made to account for flashing and burn duration effects. Relevant coldflow testing to characterize these effects and the valve system itself will be included. Open-loop testing is included as demonstration of the valve controller.

II. Background

Previous literature regarding studies on hybrid engine throttling have achieved stable, steady-state, and transient thrust control for several propellant combinations, such as HTPB + nitrous [7], hydrogen peroxide + polyethylene [8], and paraffin + nitrous [9].

Traditional methods for hybrid throttling rely on the development of regression rate and blowdown models to create relationships between thrust, chamber pressure, and oxidizer mass flow rate and thus produce a theoretical prediction of thrust. In hybrid rockets, regression rate is typically represented by the power law [10]:

$$\dot{r} = aG_o^n \tag{1}$$

However, Peterson shows solid fuel has a nearly linear regression rate with oxidizer mass flow rate. This yields a self-compensating effect that significantly decreases the complexity of the equipment required to achieve stable thrust [7]. Nonetheless, regression-based approaches require extensive testing to determine empirical relations and constants such as the burn rate coefficient and the regression exponent. Additionally, a reliance on the self-pressurizing properties of nitrous can lead to additional considerations necessary to offset the consequences of tank blowdown, such as additional terms in the valve controller to correct for pressure changes. A solution to this problem is to externally pressurize the oxidizer with an inert gas, which results in the addition of pressurant systems that can add weight and complexity to the feed system hardware. This is often much simpler for analysis of flow testing, and is preferred for ground systems, where weight is not an issue. An example of such a system is that of Peterson et al. [7]

Peterson et al. has provided substantial advancements in the feasibility of deep throttling for hybrid rocket systems using nitrous oxide and HTPB. To counter the pressure-drop effects of nitrous oxide and minimize run-to-run variability, the nitrous tanks were pressurized by gaseous helium. The study utilized open and closed-loop throttle control tests of both coldflows and hotfires. Testing consisted of open-loop motor tests to better classify their system parameters and throttleability and closed-loop motor tests to track their step (10% valve angle increments) and ramp profiles (within the effective throttle regime of 30% to 70%). Data from these initial open-loop coldflows was used to approximate a relation between chamber pressure and thrust. From these relations, an integral controller was built for coldflow testing, while a PI controller was used for hotfire testing. Peterson mentions that a derivative term was built into the controllers, but found the PI controller to be sufficient for valve control. Gain tuning of these controllers was done through a custom simulation model and was consequently applied to all tests. Open-loop and closed-loop tests were validated using both chamber pressure and thrust as throttle controller feedback. Ultimately, chamber pressure was selected as the main feedback measurement over thrust as thrust feedback cannot be reliably measured in flight systems and is only viable for ground-based test stands. As a related constraint for application of the system, test stand harmonic noises can interfere with thrust measurements.

Conducted tests were relatively short in duration at 10-14 seconds for the hotfire portion of the campaign, and therefore did not account for long-term effects of fuel grain regression. However, the effects of erosion are mentioned, namely that the thrust-feedback controller can account for changes in chamber pressure over time due to erosion. This is due to the direct control that the controller has over thrust, whereas the chamber pressure-feedback controller cannot handle the effects of erosion due to the relation between chamber pressure and thrust being determined before the test begins. Peterson notes this drawback and proposes a solution via a live adjustment of the chamber pressure/thrust relation. However, this approach is nontrivial, as it requires in-flight thrust estimation, which then requires precise accelerometer data and must account for propellant drain and structural modes. For the purposes of Peterson's tests, erosion was ignored as a separate variable for the chamber pressure-feedback tests and absorbed into the PI controller. Even without additional considerations, chamber pressure-feedback controllers maintained thrust levels within acceptable deviations below that of uncontrolled thrust. Ultimately, tests concluded that the most effective controllers not affected by erosion maintained mean thrust within 0.53% of target thrust.

Waxman et. al [11] similarly provided advancements to the development of hybrid rockets, specifically with the use of self-pressurizing rocket propellants and nitrous oxide. One of the key takeaways this study provides is the viability of carbon dioxide (CO_2) as an alternative to nitrous for coldflow testing purposes. This similarity is shown in Solomon [12], where the critical similarity variables include near identical molar masses, gas constants, and relatively similar critical and vapor pressures. Solomon additionally corrects the Dyer (NHNE) model first proposed by Dyer et. al. [13] to more accurately represent when the incompressible equation dominates the NHNE model. Waxman takes this corrected model and applies it to several flows across injectors with both carbon dioxide and nitrous. The results of these flows are interpreted to confirm that the species are analogous, as the C_d for both species is within 5% of each other, and the critical mass flow rate is within 10%. This confirmation is particularly relevant for throttling system development, as tests for key system parameters such as mass flow rate and discharge coefficient can be conducted using CO_2 instead of N_2O. For preliminary testing, this is preferred due to the relative accessibility of CO_2 as a species because of its cheaper cost, enabling more tests to be conducted with a CO_2 tank as compared to a nitrous tank. Moreover, nitrous, while considered much safer than alternative oxidizers, is still susceptible to rapid exothermic decomposition and can lead to pressurized vessel explosions in extreme cases. Waxman references these risks, and conducts most tests with CO_2, opting only to run N_2O tests at a bunker located in NASA Ames, maintaining a safe distance of 150 feet from the test stand.

These findings inform the present work, which builds on Peterson's work and utilizes similar hardware to that of Velthuysen [14]. Testing campaigns consisting of coldflows and hotfires are derived from both Peterson and Waxman, and CO_2 is accordingly used as an alternative to nitrous for preliminary testing to characterize discharge behavior, determine valve authority, and establish viability of the throttling system as a whole.

III. System Overview

Before implementing the throttle valve, a propellant feed system (PFS), shown in Fig. 1 had been built with direct piping to an engine designed for a 1000N output without intermediary flow control. Addition of the throttle valve to the PFS consisted of attaching the valve via adapters upstream of the injector, which was assumed to have a negligible effect on the change in pressure across the valve. Pressure transducers were also placed upstream (M1-PT) and downstream (M2-PT) of the throttle valve for characterization of the pressure drop in order to derive discharge coefficient and assess mass flow rate. This overview will describe the iterative design of the Main Throttle Valve (MTV) system, as well as relevant control algorithms and derivation of intermediary relations for a feedback system.

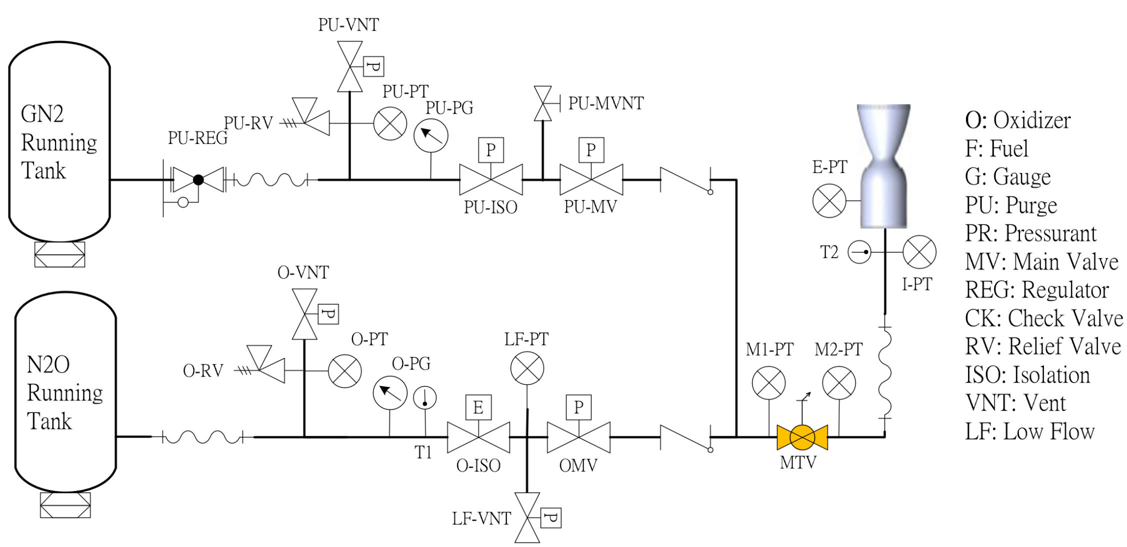


Fig. 1 P&ID of PFS

A. Hardware Overview

Main considerations for valve selection were a flow coefficient (C_v) capable of meeting the required mass flow rate and linearity of the flow profile. The mass flow rate necessary to achieve 1000 N of thrust was determined to be 0.56

kg/s with the assumption of choked flow through the throat of the nozzle and was calculated using the equation for mass flow rate of an ideal choked compressible flow:

$$\dot{m} = \frac{Ap_t}{\sqrt{T_t}}\sqrt{\frac{\gamma}{R}}(\frac{\gamma+1}{2})^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{2}$$

All throat properties were derived from nozzle sizing, the equations for which are beyond the scope of this paper.

The aforementioned considerations led to the selection of a ball valve as the primary throttling mechanism. Ball valves are preferred to alternatives such as globe valves and butterfly valves due to their large C_v values and simplistic actuation. Furthermore, ball valves come in a variety of port geometries, such as full port, standard port, and the selection for this paper, a V-port. V-ports are ideal for scenarios involving throttling due to turbulence reduction upon initial open because of their wedge-shaped ports and their more linear flow profiles [3]. This simplifies controller development due to less complex relations within the effective throttling regime. V-port valves come in a wide variety of angles to meet varying flowrate requirements, with the tradeoff of sacrificing profile linearity when using larger angles.

Figure 2 shows this relation by plotting the flow rate of an ideal liquid at the operating conditions of the feed system as a function of the valve angle. Valve angle is shown here as a percentage of valve opening (where a fully opened valve corresponds to 100%). Flow rate is calculated here from Eq. (3) [15]. It is noted that larger increases in flow rate begin after 40% open, indicating the beginning of an effective throttle regime.

$$Q = C_v\sqrt{\frac{\Delta P}{SG_{N_2O}}} \tag{3}$$

and the C_v given in the manufacturer sheet of three Valworx ½" V-Port Ball Valves of varying port angles. [16]

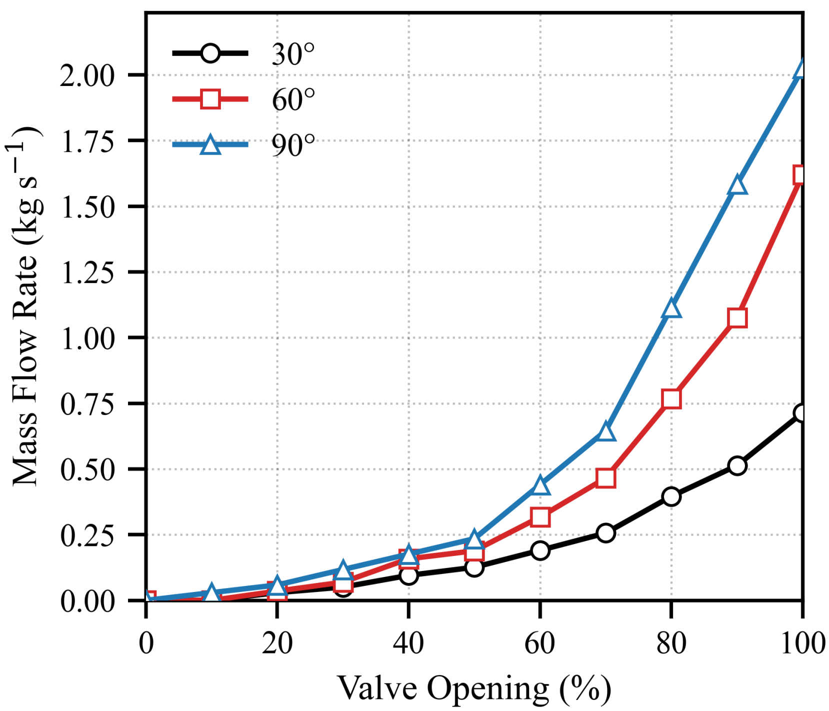


Fig. 2 Comparison of varying v-port angles

While all valves met the mass flow rate requirement at 100% open for an ideal liquid, a correction for mass flow rate drops due to flashing was necessary to accommodate for nitrous's two-phase properties. As part of preliminary design considerations, a 25% loss was assumed as a conservative estimate based on higher-end estimates of flashing loss from literature review. After these corrections, the 60 degree and 90 degree valves remained as viable options. Ultimately, the 60-degree V-port was selected for the purpose of balancing flowrate and profile linearity. [17]

As the MTV was built for initial operation on a ground-based test stand, weight was not given consideration for the current design. It was decided that optimization would take place after characterization of all components on the system. Future considerations for implementation on a VTVL vehicle regarding weight and sizing of components will be discussed later in this paper.

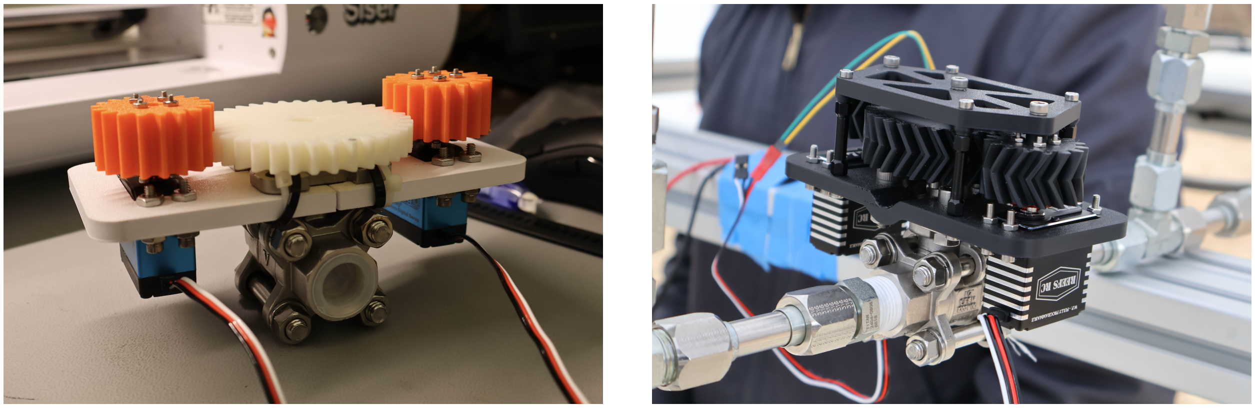
Considerations for the actuator used to control the valve included operating torque, actuation time, power draw, cost, and programmability. Servos were selected as the actuator of choice due to their precise nature for relatively low cost. Within the available budget, most servos failed to meet the torque requirement of 50 lb-in. specified by the datasheet for the selected valve. As such, a herringbone gear train setup with a 1:2 ratio, with the larger gear positioned on the valve stem, was implemented to double the torque with the tradeoff of doubling actuation time. However, at this torque spec, many servos had actuation times well under the 0.5 second requirement imposed by GNC, negating the need to select for actuation time along with torque output. For stability and redundancy, a servo (with gear attached) was placed on both sides of the central gear, ensuring smooth operation. The selected Reefs RC Triple7 Direct Power Brushless Servo [18] met the altered torque requirement of 25 lb-in., with an operating torque of 41.7 lb-in. at 11.1V input.

Table 1 MTV Component Specifications

Parameter	**Value**
Valve Specifications	
Maximum valve operating torque	49.6 in-lb
Valve pipe size	0.5 in
Valve weight	1.2 lbs
Valve C_v	5.5
Valve rated pressure	1000 psi
Servo Specifications	
Maximum servo operating torque	41.6 in-lb
Voltage input	11.1 V
Actuation time (full turn)	0.1 s
Servo weight	3.12 oz

Initial prototype assembly utilized a 3D-printed mount to position the servos and valve such that the gears meshed with minimal error. This prototype was found to wear away at the valve stem-gear interface, inducing play in the servos and thus leading to inaccuracies when actuated by the servo. Additionally, the mount was found to creep under the weight of the attached components. To solve these issues, another iteration was developed, this time with metal flanges added to the gears to interface with the valve stem. In addition, this mount included a top plate, attached by standoffs, to prevent creep over time due to weight of the assembly by reinforcing the structure. Gear sizes and teeth number were determined after modeling the subsystem in CAD using Eq. (4), a sizing equation for the distance between two gears. A sufficient center distance C from the center gear to servo gear was determined to be 54mm to account for the sizes of the valve and servos and appropriate buffer. Assuming a standard module m of 2mm and a gear ratio (N1/N2) of 2, the number of teeth was determined to be 36 for the central gear and 18 for the outer gears. Following the gear ratio of 2, the central and outer gears were accordingly sized at 36 and 18mm in diameter, respectively.

$$C = \frac{D_1 + D_2}{2} = \frac{m(N_1 + N_2)}{2} \tag{4}$$



(a) Initial iteration of MTV **(b) Current iteration of MTV**

Fig. 3 MTV Designs

B. Avionics and Software Overview

To characterize the pressure drop across the MTV, accurate measurement and logging of the upstream and downstream pressure values are accomplished using pressure transducers (PTs). JPT-131 PTs are used, which output an analog 0-10 VDC signal proportional to the Full Scale Output (FSO) of the sensor, 0-100 bar. The primary motivation for using the JPT-131 PTs involved availability, as several were available in organization inventory prior to the MTV testing campaign and operating pressure range. For static testing, pressures strictly under 65 bar are expected and the upper range of the operating range provides a comfortable tolerance of over 150%. Oxidizer temperature is also measured at the source and downstream using XTP50N-030-N40140F temperature sensors from AutomationDirect. This yields 4-20 mA current signals proportional to -65 °C to 65 °C. Sensor data is logged at a rate of 500 Hz using the myDAQ from National Instruments. Sensor outputs are fed to the ±10 VDC analog inputs of the myDAQ, converting the temperature signal to 1-5 VDC using a 250 Ohm resistor prior to acquisition. The pressure data is scaled by a factor of 10 to account for pressure, in bar, and the temperature data is translated to Celsius by a custom scaling function in LabView before being written to a text file. This data is later parsed using a Python script for post-processing and analysis.

Due to constantly changing conditions throughout the propulsion system, there is a need for real-time onboard control of the MTV to get to and maintain target chamber pressure, and therefore thrust. Because these conditions are rapidly evolving, lightweight and fast control is required. For these reasons, a PID controller augmented with a lookup table has been implemented. After characterizing the system with several hotfires, mapping of an approximate relationship between MTV valve angle and thrust is conducted. The MTV valve can be actuated to this approximate position without excessive computational overhead. When the valve approaches its targeted position, the PID begins control using feedback from pressure transducers in the engine to fine-tune thrust control. Due to difficulties tuning the PID in real time during a hotfire, a simulation of the MTV and the Ziegler-Nichols method to tune the gains for the PID controller is utilized. A simple simulation of the MTV in Python will first be created using parameters obtained from a CAD design of the MTV, parameters from the spec sheet for the servos controlling the MTV, and mass flow values from cold flows. Initial PID gains can be found using this simulation. These values are then used as a starting point for the Ziegler-Nichols method. Since there is a relatively limited number of hotfires possible to run, this method is best suited to get the best PID tunings from lower number trials. Pressure and thrust data are recorded during the hotfire, allowing evaluation of the effectiveness of tunings by integral absolute error, overshoot, and settling time.

IV. Results and Discussion

This section presents the experimental results of the throttle development campaign and evaluates the performance of the MTV system. The testing campaign currently consists of open-loop coldflow testing, with hotfires and closed-loop tests planned for future work. These tests provide empirical relations and observational data required for characterization and validation of the system. An outline of future tests and their relevance will be detailed in a later section.

A. Open-Loop Coldflow Testing

Five total open-loop coldflow tests have been conducted to date. Of these, three used CO_2 as a nitrous alternative. As previously mentioned, carbon dioxide shows similarity as a species to nitrous oxide and is a viable replacement for coldflow testing due to its two-phase properties. Four tests were step profiles intended to characterize the relation of thrust to valve angle in order to find the region where the valve has most control authority. A static coldflow where the MTV remained at 100% for the duration of the test was also run. This short test allowed for derivation of the discharge coefficient, allowing future mass flow rate calculations during throttling tests when mass flow rate cannot be calculated from the difference in tank weight.

C_d was calculated using the equation for mass flow rate of an injector:

$$\dot{m} = C_d A_{inj} \sqrt{2\rho\Delta P} \tag{5}$$

$$C_d = \frac{\dot{m}}{A_{inj}\sqrt{2\rho\Delta P}} \tag{6}$$

These equations, while generally applied to incompressible flows, is applicable here as it is assumed that the effects of flashing are condensed into the discharge coefficient. This leads to lower discharge coefficients as compared to straight-edge orifices with compressible flow, which experience discharge coefficients around 0.6 [19]. This assumption is covered in further detail by Bouziane [20].

The test was performed over a three-second interval, and mass flow rate through the MTV was determined by measuring the difference in tank mass, factoring in the remaining mass of 0.404 kg in the pipes after the test finished, before depressurization occurred. This was done by finding the total volume of the piping before the main valve that controlled flow from the tank and multiplying by density of saturated nitrous at testing conditions. The nitrous tank lost a total of 1.44 kg of nitrous over the duration of the test. Over the three-second interval, 1.036 kg of nitrous traveled through the MTV, yielding a mass flow rate of 0.345 kg/s. For this calculation, the MTV is analogous to an injector, so A_{inj} refers to the port area of the MTV at 100% open, which had been calculated using SolidWorks to be 73.55 mm^2. The density of 965.72 kg/m^3 was obtained via a NIST database lookup at operating conditions of 7.34° Celsius and 1.68 bar. System pressure for the density lookup was calculated as the average of the average pressures both upstream and downstream of MTV. Pressure drop was calculated as the difference of the average pressure upstream and downstream of the MTV using pressure transducer data. Final C_d value was determined to be 0.26. This value is comparable to Bouziane [20], who similarly found discharge coefficient of an injector using nitrous to be 0.32.

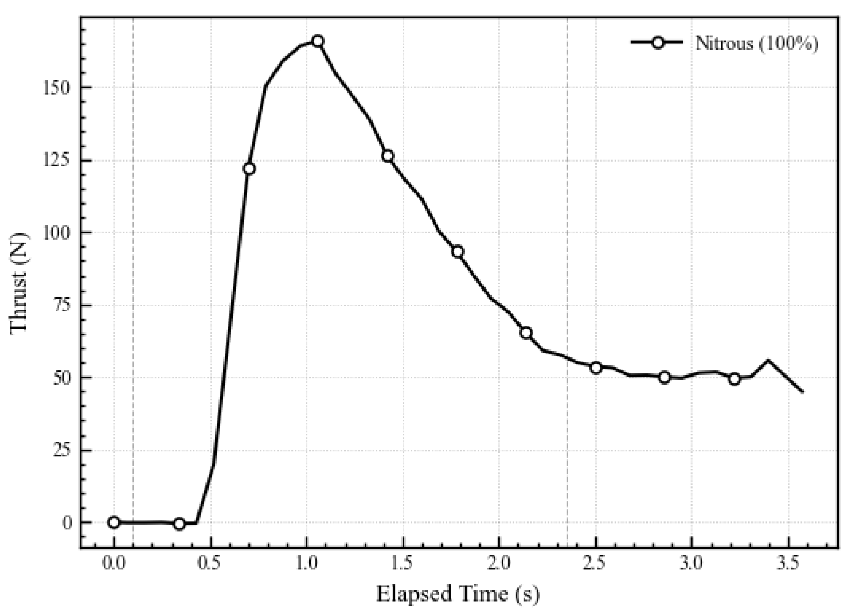
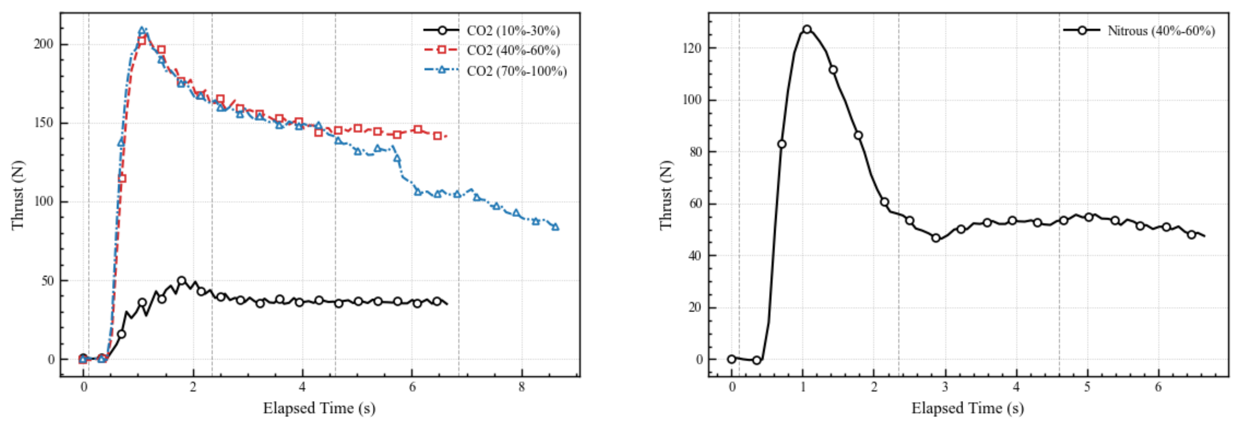


Fig. 4 Nitrous Static Coldflow Data

Throttling tests were split into profiles consisting of three or four 10% increments of the valve as to reduce test duration. As the carbon dioxide and nitrous tanks were not externally pressurized, this was intended to minimize the effects of tank blowdown. Three tests were used to cover the full range of the valve using carbon dioxide, with profiles from 10%-30%, 40%-60%, and 70%-100%. All angles were held for 2.25 seconds to allow for stabilization of thrust. A point of note is that the third test caused the CO_2 tank to run out of liquid, evidenced further by the sudden drop in thrust halfway through the third valve angle change.

In addition, a nitrous coldflow with a 40% -60% step profile was also run to validate similarity to carbon dioxide and assess any variations in thrust. As nitrous was limited, the 40%-60% profile was selected due to it being within the most effective throttle regime, as shown in Fig. 2.



(a) Carbon Dioxide Coldflow Data **(b) Nitrous Coldflow Data**

Fig. 5 Coldflow Throttle Tests

From the carbon dioxide coldflows, it can be seen that the throttling demonstrates a monotonic increase of thrust, with more mass flow rate (seen through an increase in thrust) at more open valve angles. Notably, a large jump is seen within the effective throttle regime above 40%, and a smaller increase is seen below this angle. A possible explanation as to why little change is seen between the second and third coldflow is that the load cell used to measure thrust may not be sensitive enough to register smaller changes in thrust from adjustments outside the effective throttling regime. This is coupled with the effects of tank blowdown, which impact effective thrust and minimize throttling changes.

It is noted that thrust graphs remain relatively stable and even exhibit decay despite being throttled. This is attributed to the lack of a pressurant system on the oxidizer tank. The effects of tank blowdown cause a weaker tank pressure as the liquid runs out, reducing the mass flow rate to the point where the MTV cannot compensate by throttling. Another key observation is that nitrous failed to meet the same amount of peak thrust as CO_2. This is assumed to be due to nitrous's tendency to have reduced mass flow rate as it has properties that contribute to more pronounced flashing within the tank. The thrust spike seen in all coldflows is the byproduct of initial pressurization before the system reaches steady-state operation. This can be eliminated with a ramp profile that causes a gradual flow increase. Therefore, this is not a concern for controller development.

B. Future Considerations

Results presented in this paper represent an early stage of development for the MTV. The MTV requires extensive testing in order to fully characterize all relations necessary to successfully develop an in-flight controller. The tests detailed in this paper have provided a foundational understanding of the flow dynamics of the system and can be used to start development of a throttle controller using real data to match the simulations. However, drawbacks of current tests have been noted—namely, the blowdown effect resulting in obfuscation of normalized thrust data and whether throttling affects it. Future tests will incorporate a gaseous nitrogen pressurant system in order to minimize these effects, as well as reduce flashing of nitrous by maintaining a higher feed pressure of 60 bar, in order to simulate tank conditions for the lander vehicle in flight.

Ultimately, the goal of the MTV testing campaign is to provide a clear mapping between valve angle and chamber pressure, as chamber pressure is the only reliable sensor available during flight to calculate thrust. Determining the intermediary relations of valve angle to mass flow rate and mass flow rate to thrust is unnecessary as thrust is proportional to mass flow rate. Pressure data throughout the system was collected for this test, but results mapping valve angle to chamber pressure were omitted as they were deemed inaccurate and would not further controller development. This is once again due to the thrust data being affected by blowdown, which will not occur in any future tests, and so developing a blowdown relation is unnecessary.

The MTV testing campaign, beyond the tests outlined in this paper, includes more open-loop coldflows and hotfires, as well as closed-loop tests for validation of the throttle controller once finished. Ideally, the tests already run will be conducted again to assess the effects of the tank maintaining a constant pressure, as well as more nitrous coldflows to ensure more accurate data that will closely adhere to the operational runtime. Open-loop hotfires serve the purpose of informing the regression rate constants and determining whether fuel grain regression is a factor that will severely affect the ability to throttle or whether it can be enveloped into the PI controller. Similarly, erosion data collected will serve the same purpose, and implementation of the live conversion between thrust and chamber pressure can be explored to assess effectiveness of maintaining stable thrust. Upon completion of open-loop testing, closed-loop testing will subsequently occur, and coldflow tests will focus on tuning and validating the throttle controller. Gain tuning is a vital aspect of this controller, and finding the correct values will be critical to ensuring minimal oscillation and target thrust deviation. Ideally, gain tuning can be done via simulation using collected coldflow data, but observed data is necessary for validation due to combustion dynamics that cannot be replicated exactly. Finally, closed-loop hotfires serve as the final set of tests for the ground-based feed system. These tests confirm whether the controller can handle live effects of regression and erosion and will allow for updating of PI gains to match that of a true operational run.

Additional considerations for the MTV pertain to GTPL's development of a hybrid rocket lander. During flight, conditions can deviate significantly from what is expected on ground-based stands, and considerations for component selection on a flight-based feed system shift towards efficiency and weight optimization. Weight optimization for the MTV is difficult as most components have no lighter alternatives, but one path that can be taken is replacing the current V-port ball valve with a low-profile, full-port ball valve. Low-profile ball valves utilize a single or double-piece construction, making them lighter, but do not come in a V-port format. This introduces the problem of reduced flow linearity, but depending on how accurate the mapping of chamber pressure to thrust is for flight conditions, flow linearity may not be a crucial factor in deciding how effective the MTV is. Currently, the MTV is within the current estimated mass budget for the lander and does not require any changes.

V. Conclusion

This paper presents the development and initial characterization of a servo-actuated, closed-loop nitrous oxide throttling system for a hybrid rocket lander intended for surface hop maneuvers. The system was designed to address the unique thermodynamic challenges posed by nitrous oxide operating near its vapor pressure, specifically the onset of two-phase flashing instability that reduces oxidizer usability and degrades throttle control authority.

A 60-degree V-port ball valve was selected as the primary throttling mechanism for its balance of mass flow capacity and profile linearity within the effective throttle regime. A herringbone gear train was implemented to meet valve torque requirements while maintaining rapid actuation times compatible with GNC constraints. Iterative mechanical design resolved early issues with valve stem wear and structural creep, yielding a robust assembly suitable for continued ground-based test campaigns.

Open-loop coldflow testing with both carbon dioxide and nitrous oxide established a foundational characterization of the system. Results demonstrated a monotonically increasing thrust response with valve opening angle, with the most significant control authority concentrated in the 40%–80% valve opening range. The discharge coefficient of the MTV was empirically determined to be 0.260 at fully open conditions. Carbon dioxide was validated as a viable alternative for nitrous oxide in preliminary testing, consistent with prior literature, with observed thrust levels showing general agreement between the two species. Tank blowdown was identified as an obfuscation factor in current test data, and future correction via a pressurant system has been planned.

Future work will expand the testing campaign to include pressurized open-loop coldflows and hotfires to characterize regression rate and erosion behavior, followed by closed-loop coldflow and hotfire tests for PI controller tuning and validation. The ultimate objective is to establish a reliable mapping between valve angle and chamber pressure suitable for in-flight thrust estimation, enabling stable thrust control throughout lander operation.

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