

Thrust augmentation of a solid rocket motor by means of inert gas injection.



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Introduction

Historically, solid rocket motors have been very difficult to control once it is ignited, unlike liquid rocket systems. The ability to control the thrust of a solid rocket motor could be applied to missiles and orbital insertion motors.

Theoretically, by injecting a large mass flow of nitrogen quickly into the combustion chamber, the chamber pressure can be rapidly raised, increasing the rate of combustion.

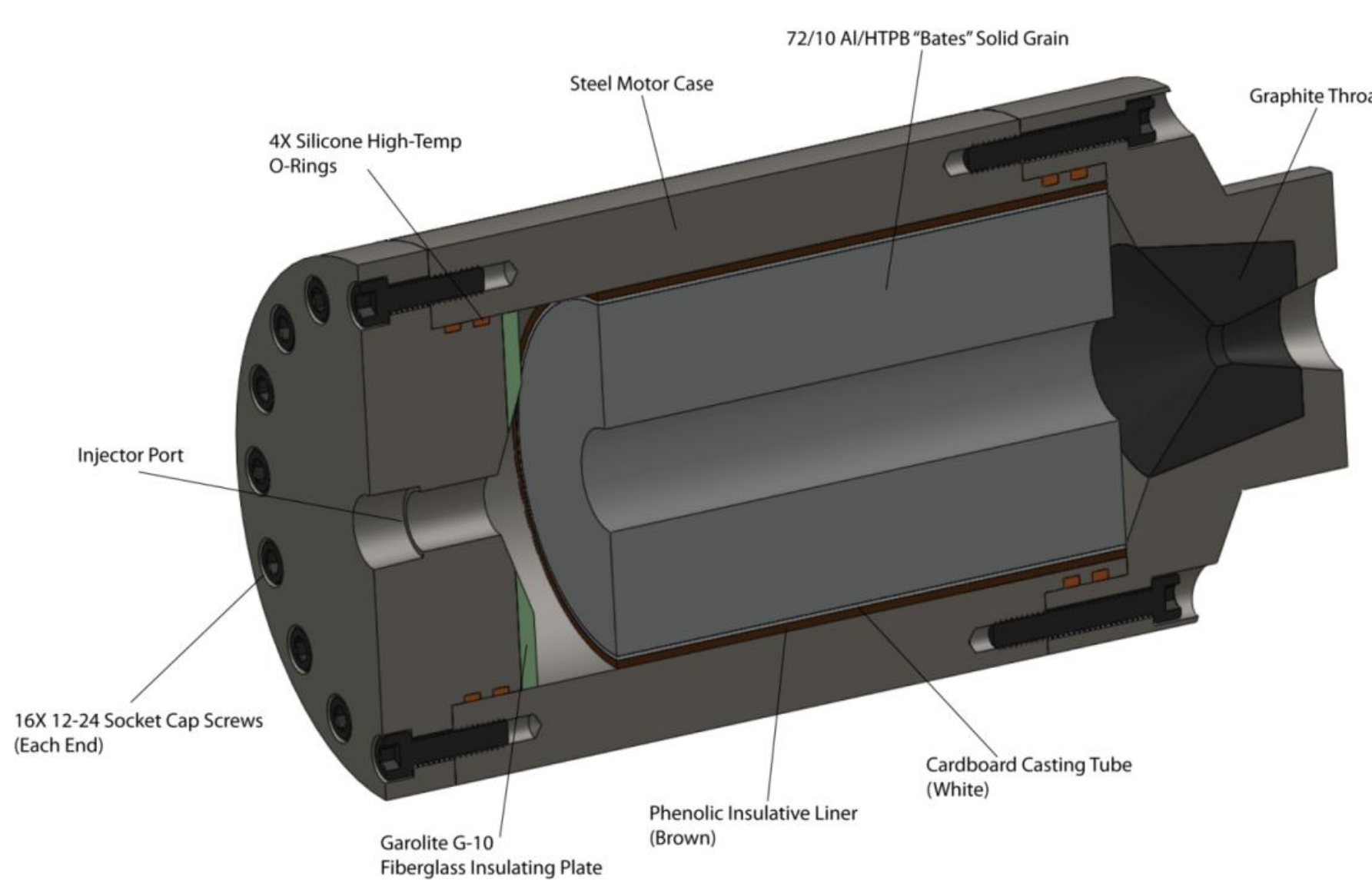


Figure 1. Illustration cut-out of the motor case, with the solid propellant in light grey, the nozzle in black, the injector port on the left side, and the heat-sink steel motor case in dark grey around the outside.

Materials and methods

The thrust stand, thrust collector and motor case were made of steel, designed to at least a F.O.S. of 5, as shown in Fig. 2. The solid motor is a cylindrical core and double-end burning configuration of 72% Ammonium Perchlorate, 10% Aluminum, and 15% HPTB binder. The nitrogen inert gas is injected at the head end of the motor using a remote access solenoid valve. The chamber pressure and nitrogen source pressure are recorded using an NI DAQ USB system

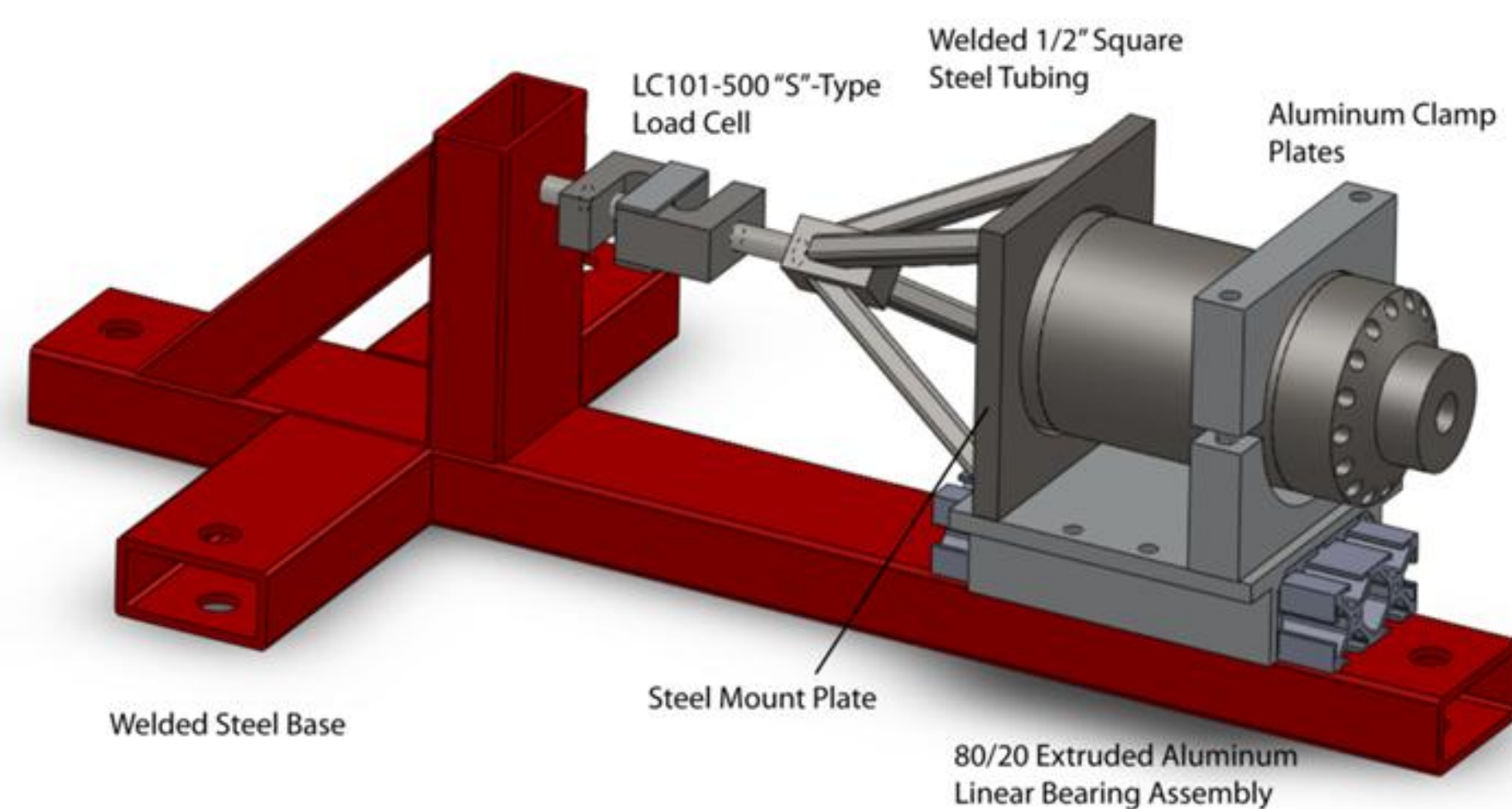


Figure 2. Illustration of thrust stand, thrust collector, and motor case. All equipment had a F.O.S. of 5+.

Results

The project involved creating a theoretical model to compare the empirical results from the hot-fire testing to see how closely one can anticipate the thrust increase from the inert gas injection. A comparison of the theoretical and empirical thrust versus time is graphically depicted in Fig 3. Run #3 is the baseline test without any gaseous injection.

Comparison of Theoretical and Empirical Thrust Data for All Test Cases

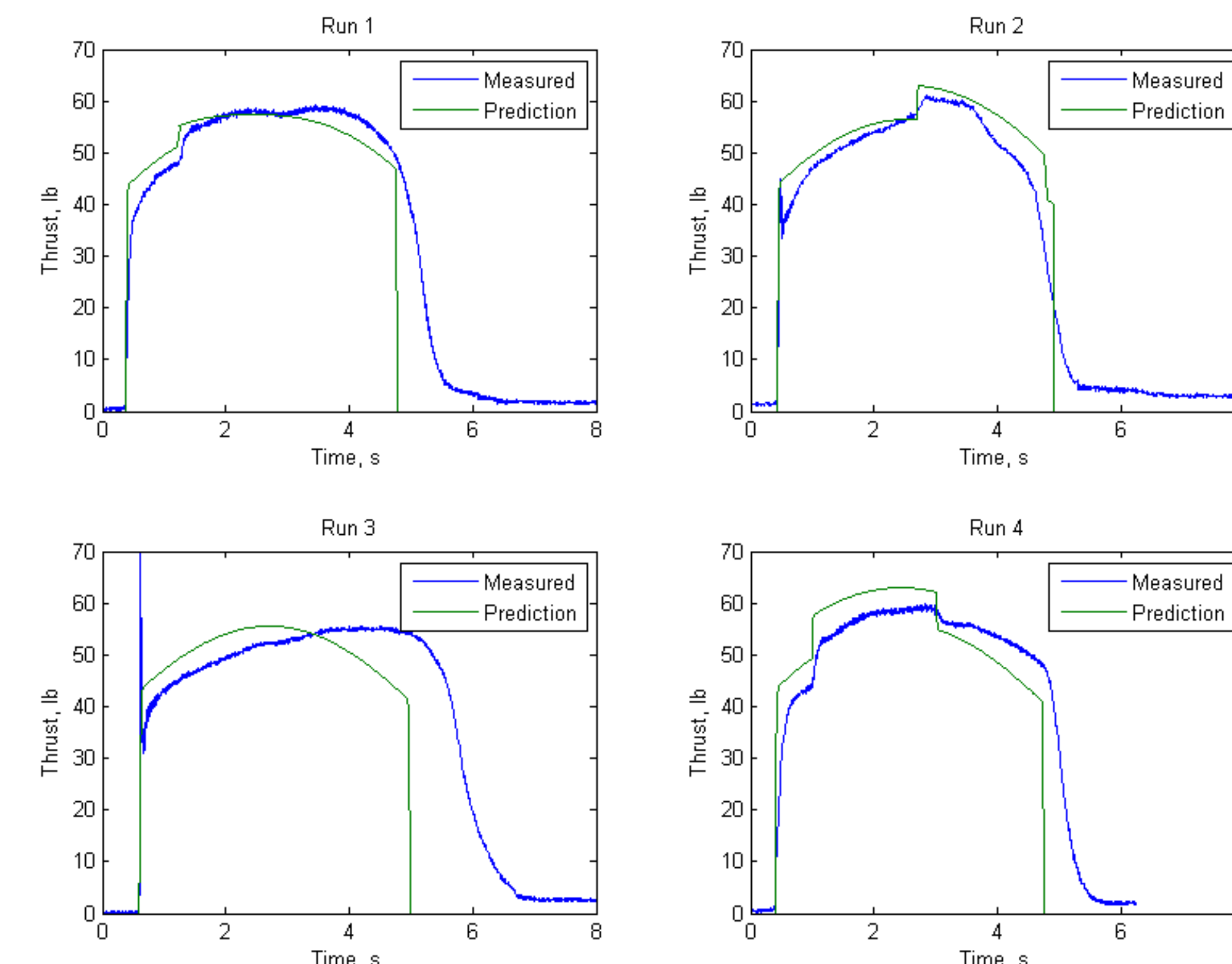


Figure 3. A graphical comparison of the predicted thrust with the measured thrust from the experimental testing. Run #3 is the baseline test to establish the normal thrust profile. Run #4 demonstrated the largest percentage thrust increase and illustrates the thrust decrease at injection cutoff.

The testing regime, which consisted of three injected cases and one baseline test, successfully showed the ability to increase the thrust of the solid rocket motor. As you can see from Fig. 3, the measured thrust was substantially less than anticipated on all cases, which can be attributed to a non-uniformity in the length of each test grain. Run #4 was especially interesting because it illustrated what happens when the gaseous injection of the nitrogen is cut off. In the computer model, the thrust would negatively change as much as it had positively changed when the injection started. However, as the bottom right graph in Fig 3 illustrates, the thrust decrease at cutoff was substantially smaller than the thrust increase at the start of injection. This is further explored in Table 1, which numerically compares the expected and delivered results from Run #4.

Take note in Table 1 that the computer model matches up well with the percentage thrust increase at the initiation of injection but fails to correctly predict the thrust decrease at injection cutoff.

Table 1. Numerical comparison of the theoretical and empirical results of Run #4, including thrust increase at injection and decrease at cutoff.

Run 4	Experimental	Analytical
Avg. Thrust [lbf]	50 ± 3	54.6
Max Thrust [lbf]	60 ± 1	63.0
Avg. Pressure [psia]	800 ± 80	569.3
Max Pressure [psia]	960 ± 30	654.4
ΔThrust @ Injection [%]	23.9 ± 0.5	23.1
ΔThrust @ Cutoff [%]	1.55 ± 0.08	14.2

Note the data match-up on injection but not at cutoff.

One unexpected observation, distinctly shown in the graphical comparison of Run #4's thrust and chamber pressure in Fig 4, is the steady dip in chamber pressure during the middle of the burn. This dip in chamber pressure, while not designed for, was seen in all tests, including the baseline test, Run #3. This pressure loss, inherent in the solid grain profile, could account for the smaller change in thrust at cutoff.

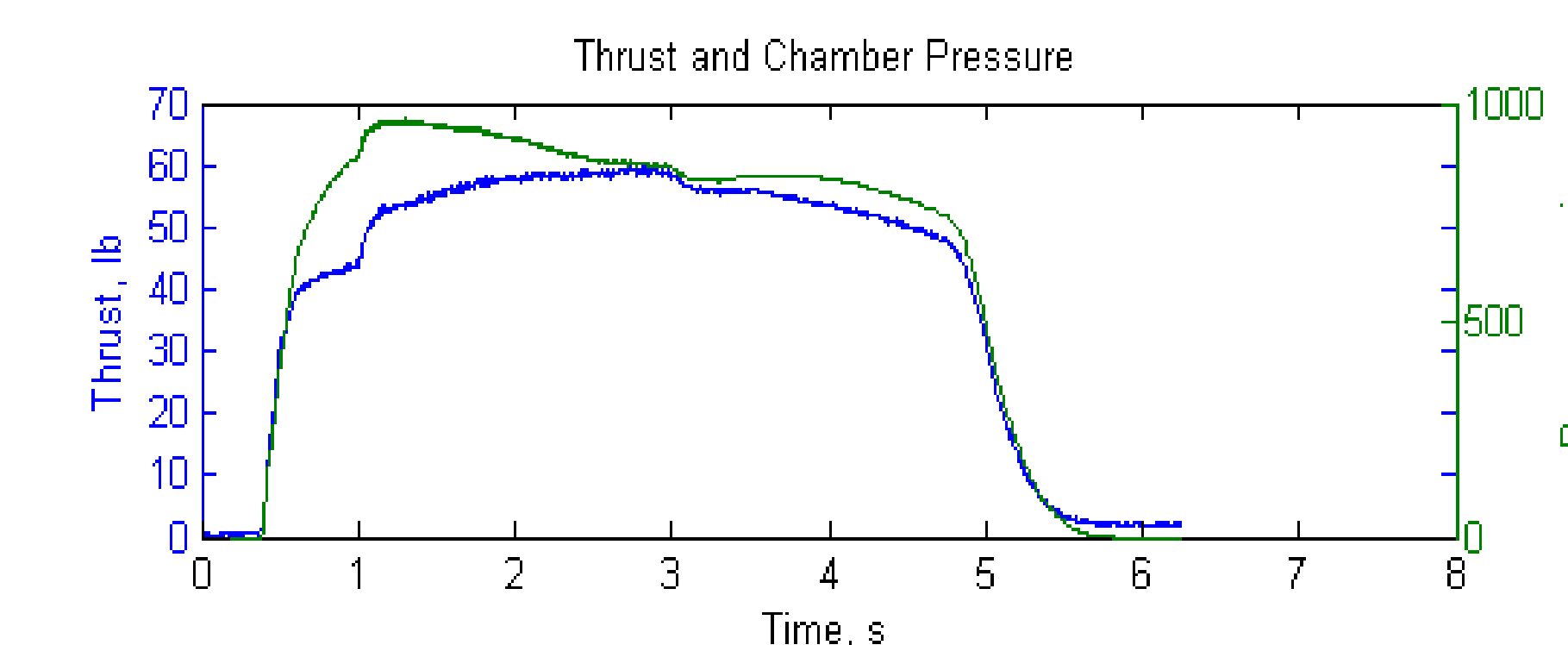


Figure 4. A graphical representation of the thrust and pressure versus time for Run #4, for reference with Table one. Note the instantaneous pressure and thrust increase at ~1 second.

Another unexpected result from the testing was the overall higher than anticipated chamber pressure, also highlighted in Table 1. This higher overall chamber pressure, independent of the gaseous injection, is interesting and needs to be examined further. One possible explanation for this could be a boundary layer effect, since the nozzle throat is relatively small compared to the gaseous boundary attached to the walls, which could create an effectively smaller nozzle throat than what physically exists.

Conclusions

The results from this testing regime initially validate the analytical models demonstrating the ability to increase the thrust for a short period of time with thrust increases of ~10% on neutral thrust profile and ~24% increase on a progressive thrust profile. Further testing should be done to repeat the initial results found in this testing, especially the correlation between a higher thrust increase and a progressive portion of the thrust profile.

More importantly, the testing should be scaled up to see if the higher overall chamber pressure could be attributed to boundary layer effects at the nozzle throat. Furthermore, it will demonstrate what the percentage of thrust increase is on a larger scale, and find what the relationship is between scaling and the thrust increase to determine the applicability on larger systems.

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