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A Study of the Amplitude of Pressure and Thrust Oscillations in a Lab-Scale Hybrid Rocket

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Abstract

Hybrid rockets are being studied as a potential replacement for the solid rocket boosters on the NASA space shuttle. One physical characteristic of hybrid rockets that must be understood and overcome is potentially severe pressure oscillations during combustion. Pressure oscillations inside the rocket combustion chamber lead to oscillations in the thrust of the rocket. These oscillations are damaging to potential human passengers and cargo and must be minimized. Current theories surmise that the oscillations are caused by combustion chamber geometry, oxygen feed line parameters, and/or fuel combustion characteristics. This study focuses on the role of the fuel characteristics in pressure and thrust oscillations. The standard hybrid rocket fuel is hydroxyl-terminated polybutadiene (HTPB). A fuel additive, guanidinium azo-tetrazolate (GAT), has been shown to increase thrust and impulse of the rocket when added as 15% by mass to the fuel. This study compares the amplitude of the pressure and thrust oscillations of the rocket when burning HTPB fuels and when burning GAT-added fuels. Data from several firings at oxygen flow rates from 0.018 kg/sec to 0.054 kg/sec are analyzed. Results show the GAT-added fuel combustion shows no significant increase or decrease in the amplitude of the pressure and thrust oscillations.

Introduction

The hybrid rocket facility at the University of Arkansas at Little Rock (UALR) consists of a labscale hybrid rocket motor, several transducers to measure various physical properties such as pressure and thrust, a control computer, and a data acquisition computer. The facility was originally built to investigate combustion instabilities and plume diagnostics. Several hybrid rocket fuels and fuel additives have also been studied.

The standard fuel used in hybrid rockets is hydroxyl-terminated polybutadiene (HTPB). This fuel is characterized by a low rate of regression. Several fuel additives have been studied to determine if the additives increase the regression rate and improve the performance of the hybrid rocket fuel. One such study was performed on the additive, guanidiniurn azo-tetrazolate (GAT). Results showed that GAT increased the regression rate when added in concentrations of 15%, 20%, 25%, and 30% (Wright, Wynne, Rooke, and Hudson, 1998). The highest increase in regression rate was obtained for HTPB with 25% GAT by mass added.

GAT is an organic salt with a high nitrogen content. It is a highly energetic compound due to the energy stored in the pi bond system. The regression rate of this additive is large because it is a salt. The ionic bonds of a salt are easier to break than covalent bonds, leading to a lower heat of degradation. The bond structure of GAT is shown in Fig. 1.

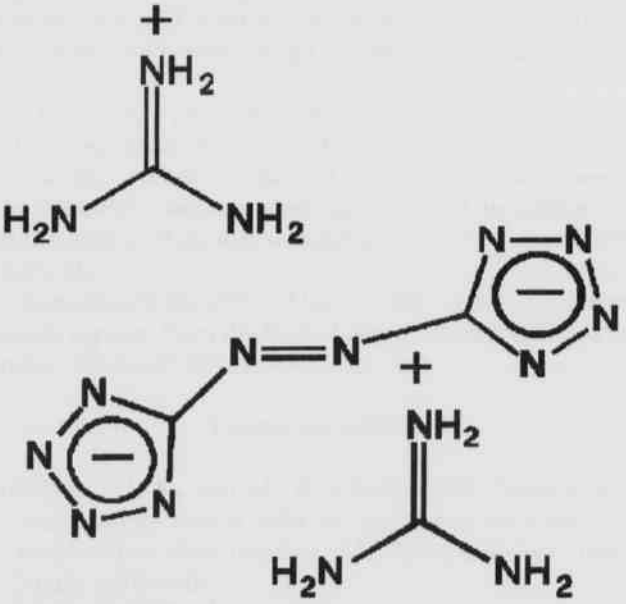

Fig. 1. The chemical structure of Guanidinium Azo-Tetrazolate (GAT).

A preliminary study of the feasibility of using GAT as a fuel additive with HTPB was presented in 1996 (Luchini, Wynne and Hudson, 1996). The results of that study detailed solutions to problems in the casting of the fuel grains and a possibility of increased regression rate, but more data was needed to fully describe the properties of the GAT/HTPB fuel mixtures. A complete regression rate study was presented in 1998 (Wright, Wynne, Rooke, and Hudson, 1998), verifying that GAT does increase the regression rate when used as an additive to HTPB fuel in Hybrid Rockets. The increase in regression rate makes GAT a desirable fuel additive to HTPB.

A study of the thrust and impulse was performed on the UALR Hybrid Rocket burning HTPB with 15% GAT by mass (Wright, Dunn, Alford, and Patton, 1999). The results showed that the GAT-added fuel produced more thrust and higher total impulse, but no significant increase in specific impulse. Another analysis of the thrust data looked at the amplitude of the oscillations.

The thrust of a rocket is the reaction force experienced by its structure due to the ejection of high-velocity matter (Sutton, 1992). The forward momentum of the rocket is equal to the rearward momentum of the ejected gases from the nozzle. Thrust is measured in Newtons of force and will be designated in this paper by the variable F. Thrust is highly sensitive to nozzle throat area (Sutton, 1992).

Pressure oscillations are a characteristic of all hybrid rocket combustion data. They can be result of combustion instabilities. Details of those instabilities are the subject of great interest. Reducing any thrust oscillations is imperative if hybrid rockets are ever to be employed in delivering valuable human and instrument cargo into space. Any strong vibrations may be harmful to passengers aboard the spacecraft. Internal rocket pressure is directly proportional to the thrust of the rocket (Sutton, 1992). Therefore, the oscillations may be studied in the thrust domain as well as the pressure domain.

Oscillations in internal pressure of the rocket combustion chamber may be a result of several factors. One factor is acoustic modes of the cylindrical pipe that composes the rocket body. Another possible source is called chuffing. Chuffing is the cyclical sloughing of a char layer of fuel as successive layers are liquefied, burned, a char layer is formed and then ejected. Chuffing is a characteristic of the fuel.

Chugging is another source of oscillations. Chugging is a factor caused by oscillations within the oxygen feed line. Tests conducted at NASA Marshall Space Flight Center (MSFC) demonstrated a low-frequency, non-accoustic chamber pressure oscillation. This oscillation was found to be generated by the motion of the oxygen feed system during firing (NASA TP-2000-209905). The UALR Labscale Hybrid Rocket Facility has been inspected by an MSFC test engineer familiar with the NASA testing. The UALR rocket was found to have a rigid oxygen feed system, and therefore eliminated the oscillations demonstrated at MSFC. Preliminary investigation of oscillations on the UALR rocket data showed a very small component of the oscillations could be attributed to chugging (Desrochers, 1997).

Materials and Methods

The hybrid rocket fuel grains were cast in paper phenolic cylinders 25.4 cm in length, 5.1 cm outer (fuel) diameter and an initial port diameter of 1.9 cm. Standard fuel grains were prepared with 85% HTPB and 15% PAPI diisocyanate used as the curative agent. A second set of fuel grains were prepared with 15% GAT by mass added to the standard HTPB and PAPI fuel mixture.

The fuel grains were fired in the UALR hybrid rocket. The gaseous oxygen flow was varied between 0.018 kg/s and 0.054 kg/s. The initial and final mass, port radii of the fuel grain, and nozzle diameter were measured for each run. The runs were set for 4 or 5 sec. However, delays in ignition caused several changes in actual length of combustion time. Pressure data was used to determine the actual length of time between ignition and shut-down.

Because thrust is very dependent upon nozzle throat diameter, care was taken to ensure that the nozzle throat diameter stayed roughly constant throughout all of the trial runs. Since the nozzle was made of graphite, exact consistency was impossible due to ablation during the runs. The nozzle throat diameter varied from 0.71 to 0.79 cm for each run.

Thrust was measured using strain gages mounted on four aluminum support beams which supported the rocket as shown in Fig. 2. The support beams were fixed on both ends, which forced them to deflect in the shape of a sigmoid curve during the firing.

The flexing beams were made from 2024-T81 aluminum with a yield strength of 448,818 kPa (Desrochers, 1997). General purpose strain gages from Measurements Group (CEA-13-125UW-350) were placed on the beams to convert strain to a voltage proportional to the thrust force. The strain gages can be seen in the photograph in Fig. 2. A two stage amplification circuit was built to collect the voltage output of the strain gages and produce a voltage between 0 and 10 volts (Desrochers, 1997). The voltage was collected by an A/D board at 1000 Hz.

The thrust detector was calibrated using a hanging weight system. Known weights between 0 and 178 Newtons were suspended from the rocket and the voltage output of the strain gages was collected. The calibration curve is shown in Fig. 3.

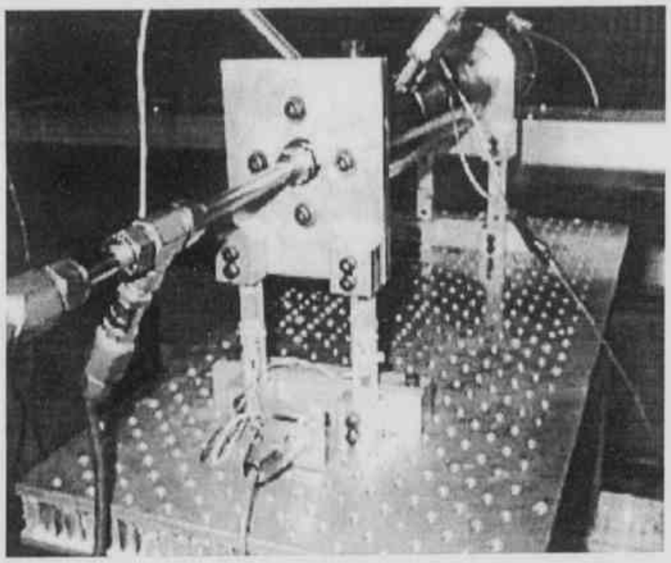

Fig. 2. A picture showing the UALR Hybrid Rocket, and the two aluminum legs supporting the rocket upon which the strain gages are mounted to measure thrust.

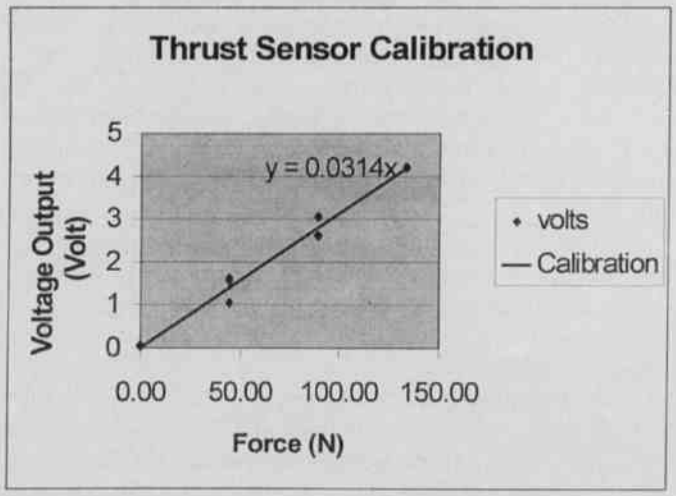

Fig. 3. Calibration of the thrust sensors. Voltage output of the strain gages as a function of known force.

Results

The thrust as a function of time was recorded for each data run. A sample plot is shown in Fig. 4. A small thrust is seen during the initial gas (oxygen and propane) flow from 0 to approximately 2 sec. A sharp increase in thrust indicates the moment of ignition, followed by several seconds of rapid oscillation during the main part of the run. The run is then shut down as the oxygen is turned off and nitrogen gas is flowed through the rocket to quench the combustion. The flow of nitrogen is responsible for the small non-zero thrust after shutdown.

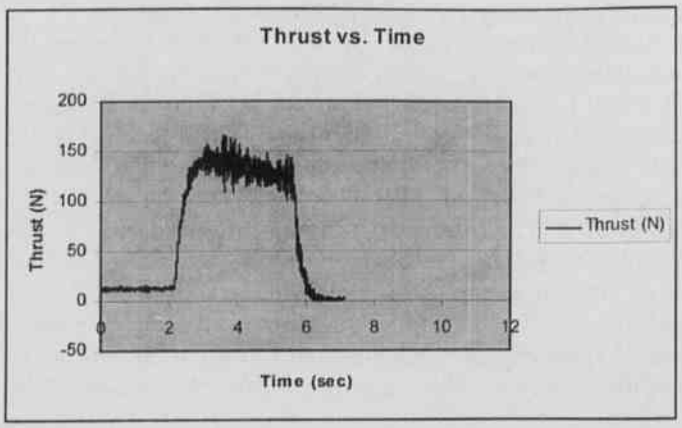

Fig. 4. A sample thrust vs. time data set.

The average and standard deviation of thrust was determined for a range between the initial start-up and the shutdown of each run. The average thrust for both the plain grain and the GAT-added grains are plotted in Fig. 5 as a function of oxidizer flow rate. The standard deviation gives a measure of the amplitude of the oscillations. The higher the standard deviation, the larger the amplitude of the pressure oscillations. Table 1 shows the average thrust and standard deviation for several different oxygen flow rates for the plain HTPB fuel runs. Also listed is the standard deviation as a percentage of the average thrust. Table 2 is similar

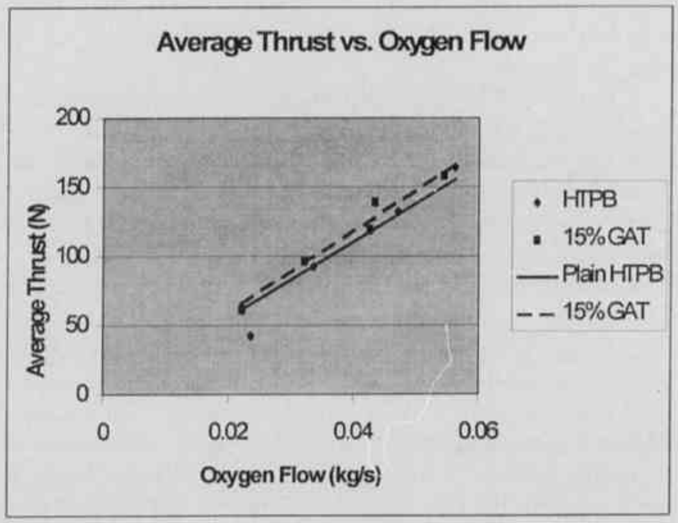

Fig. 5. Average thrust vs. oxygen flow.

Table 1: HTPB Fuel Statistics

Oxygen Flow (kg/sec)	Average Thrust (N)	St. Dev (N)	Percentage of Average Thrust
0.0236	41.95	10.49	25.02
0.0336	92.35	9.21	9.99
0.0472	131.93	10.76	8.16
0.0562	164.01	6.18	3.77

Table 2: 15% GAT Fuel Statistics

Oxygen Flow (kg/sec)	Average Thrust (N)	St. Dev (N)	Percentage of Average Thrust
0.0222	60.54	5.92	9.81
0.0322	96.48	10.23	10.60
0.0426	119.48	6.27	5.25
0.0433	138.65	10.49	7.57
0.0544	157.73	7.29	4.61

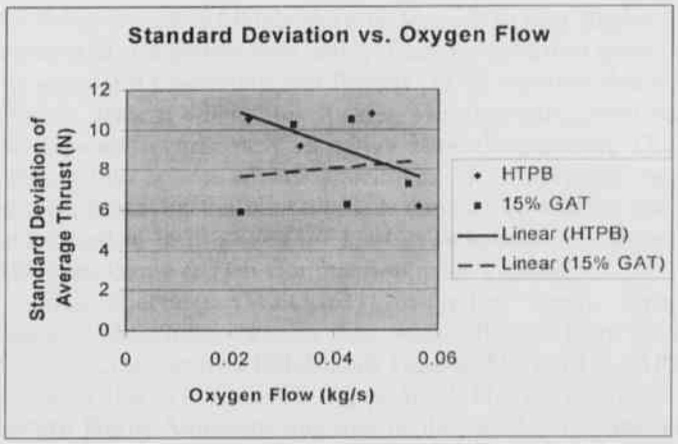

Fig. 6. Standard deviation of thrust for plain HTPB and GAT-added fuel. Shows no correlation with either fuel composition or oxygen flow.

information for the fuel with 15% GAT added. The standard deviation as a function of oxygen flow is plotted in Fig. 6. Standard deviation as a percentage of average thrust is plotted as a function of oxidizer flow in Fig. 7.

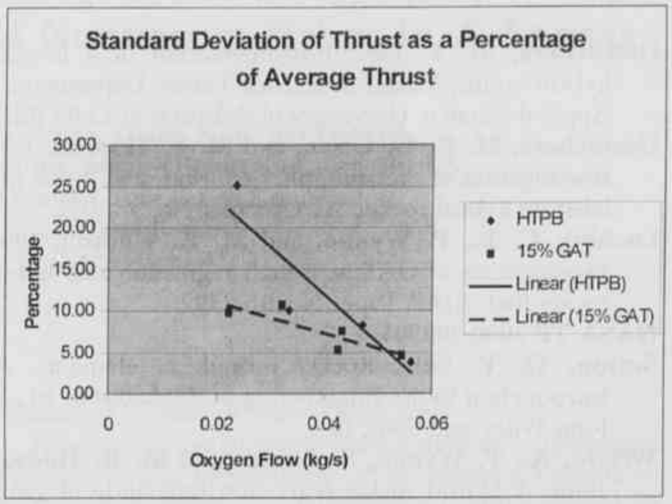

Fig. 7. Standard deviation expressed as a percentage of average thrust as a function of oxidizer flow.

Conclusions

The standard deviation is independent of oxygen flow rate and average thrust. The standard deviation is also independent of fuel. Therefore, the amplitude of the oscillations is not a factor of the fuel. Since GAT has been shown to increase regression rate and thrust, and not increase the amplitude of the thrust oscillations, it is still a viable fuel additive to HTPB Hybrid rocket fuel.

Future thrust and impulse studies are planned to investigate higher percentages of GAT in HTPB fuel. Regression rate studies indicate that 25% GAT fuel grains show the most increase in regression rate (Wright, Wynne, Rooke, and Hudson, 1998). The graphite nozzle used in these GAT studies will be replaced by a new nozzle made of a very high temperature ceramic. Variations in thrust measurements due to nozzle throat size variation will be eliminated, thus making the measurements much more accurate.

The synthesis of GAT is very time consuming and moderately expensive. Therefore, commercial use of GAT is unlikely at this time. In addition, more studies of environmental impact from combustion products needs to be conducted. NO is known to contribute to the formation of acid rain. Trace amounts in lab-scale hybrid rocket plumes would translate into a significant problem for the environment.

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