



COMBUSTION STUDIES ON PARAFFIN WAX IN GASEOUS OXYGEN AND NITROUS OXIDE

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ABSTRACT

A series of static hybrid rocket firings were done in a laboratory scale motor using paraffin wax fuel with gaseous oxygen and nitrous oxide oxidizers. A five element swirl injector was used to inject the oxidizer at the head end of the motor. A pyrotechnic igniter was used to initiate the combustion. The combustion of fuel grain was carried out for a fixed duration and at different oxidizer injection pressures. The local regression rates, average regression rates and fuel mass consumption rates were found to increase with injection pressure; however it was observed that increase in oxygen injection pressure result in dense white smoky exhaust. The local regression rate, mass consumption rate and average regression rate were found of lower value for nitrous oxide oxidizer as compared to gaseous oxygen at same injection pressure.

Keywords: boundary layer, Reynolds numbers, diffusion flame, regression rate, pyrolysis, solenoid valve, pyrotechnic igniter.

INTRODUCTION

A rocket propulsion system in which the propellant components mainly oxidizer and fuel are in different physical state prior to the combustion is known as Hybrid rocket propulsion. The fundamental difference between a classical hybrid and the liquid or solid rocket leads to a number of distinguishing characteristics. The advantages like safety, simplified throttling and shutdown, grain robustness, propellant versatility and many more, however these advantages are not enjoyed without some disadvantages such as low regression rate, low bulk density, combustion efficiency, O/F shift. From a performance standpoint, hybrid rockets, in general have specific impulse greater than solid rockets and density impulse greater than liquid bi-propellant rockets.

The key parameter influencing the design of hybrid fuel grain, and the overall hybrid motor design, is the solid fuel regression rate. Many theories have been put forward to explain the combustion of solid hybrid fuel time to time. Prominent among them are Bartel and Rannie [1], Panner [2], Moutet and Barrier [3], Wooldridge and Muzzy, Rovinowitch [4], Hauser and Pack [5] etc. The most detailed fundamental work on hybrid combustion was made by Marxman and Gelbert [6, 7, 8]. Their theory was based on turbulent diffusion flame model. According to this model, in a hybrid motor, combustion usually occurs in the boundary layer above the fuel surface rather than at the fuel surface. The boundary layer is assumed to be turbulent due to typical high injection Reynolds numbers for hybrid motors. The turbulent boundary layer is characterized by strong velocity, temperature, and species gradients normal to the surface, and mass, momentum and energy transport are dominant by the turbulent flow process. Upon ignition, a diffusion flame region forms in the boundary layer. Heat from the flame is convected and radiated to the fuel surface. This energy flux causes the solid fuel to pyrolyze and the pyrolyzed fuel vapors are then transported to the flame zone by convection and diffusion, where it mixes

with the gaseous oxidizer, which has been transported through the boundary layer from the core flow region via turbulent diffusion. The two components react in the diffusion flame, a process that provides heat to sustain further fuel pyrolysis. The fuel mass flux due to pyrolysis however blocks some of the heat transfer to the surface, which causes a decrease in the regression rate.

Many techniques have been suggested by karabeyoglu [9] *et al.*, to increase the regression rates of hybrids like insertion of screens or other mechanical devices in the port to increase the turbulence level and thus the heat transfer rates, and by adding a swirl to the incoming oxidizer flow to increase the effective mass flux and thus improving the heat transfer rate, by adding oxidizing agents or self-decomposing materials in the hybrid fuel, increasing the surface roughness of the burning surface by adding dispersed solid particles in the fuel that would burn at different rate compared to the matrix material. Unfortunately, all of these methods suffer some important shortcoming. But increased regression rates were observed with solid cryogenic hybrids. The regression rate model for these liquids have been developed by karabeyoglu and very high regression rates observed in the cryogenic tests and it was successfully predicted by this liquid layer theory which lead to the conclusion that paraffin waxes exhibit high regression rates.

The present experimental work was intended to investigate the burning characteristics of paraffin wax hybrid fuel in a stream of gaseous oxygen and nitrous oxide. Head end injection system was chosen to introduce the oxidizer in the combustion chamber and a five element swirl injector was used for this purpose. The combustion study was carried out at different oxidizer injection pressures. The parameters planned to evaluate were local regression rate, average regression rate and average mass consumption rate of fuel grain at various injection pressures of oxidizers gaseous oxygen and nitrous oxide.



EXPERIMENTAL SET-UP

Test facility

A flanged cylindrical chamber made from mild steel with length 460mm and inner diameter 75mm has been used as the combustion chamber and it was fitted with a five point swirl injector made from stainless steel at one end, and a convergent divergent nozzle made from graphite inserted in an aluminum block of length 63.68mm and throat diameter 12.25mm at the other end. The nozzle convergent angle and divergent angle were 45° and 15°, respectively. The fuel grain was processed separately and then casted inside the combustion chamber before firing.

A feed line suitable for both gaseous oxygen and nitrous oxide feeding has been designed and laid. The main oxidizer feed line was plumbed using stainless steel pipe tubing with outer diameter 6.35mm and inner diameter 3mm. A number of valves, regulators and pressure gauges were incorporated in the line to get controlled flow of oxidizer at required injection pressure.

Fuel grain processing

Paraffin wax was employed as a fuel in the present investigation. The fuel grains were prepared by melting the wax and casting in a suitable mould. Commercial wax blocks were broken into small pieces manually and the required quantity about 1 kg was kept in a stainless steel beaker. The beaker containing wax was then heated in a water bath with continuous stirring till all wax melt and becomes homogenous liquid. The liquid wax was poured slowly and in two/three installments in the mould of required shape and size.

The mould was kept for cooling under observation. It was found that the liquid wax shrink unevenly during cooling resulting in voids in the fuel grain. To overcome this problem, liquid wax was poured time to time in the mould. The mould was kept as it is for twelve hours for cooling to room temperature. After that the fuel grains were extracted from the mould manually, trimmed, checked for cracks and stored in a polythene bag to avoid contamination. The prepared paraffin wax fuel grain can be seen in Figure-1.



Figure-1. Prepared paraffin wax fuel grain.

Igniter preparation

Pyrotechnic igniter was used in the present investigation to initiate the combustion of solid fuels. It

consisted of primer and a secondary charge and an igniter case. The primary charge was a shellac propellant bead made around a three round coil of diameter 5mm of 34SWG nicrome wire and the ends of the coil were soldered with long enameled copper wire for electrical connection. The secondary charge was HTPB propellant strips each weighing approximately 0.4grams and 35mm in length. PVC pipe with one end closed and having 12 holes of diameter 3mm all along its surface was used as an igniter case. The primary bead, secondary charges were inserted properly in the case and it was then sealed tightly using an adhesive tape. The ignition delay of the igniter was found to be about one sec. It is satisfactory for static testing of hybrid motor.

Experimental procedure

The pressure regulator in the feed line was adjusted at the desired oxidizer injection pressure during firing with solenoid valve in off position. The combustion was initiated by switching on the ignition current and solenoid valve was switched on as soon as the igniter fired and the combustion was terminated after a lapse of pre-requisite duration by switching off the solenoid valve. The combustion of the fuel grains was carried out at four different oxidizer injection pressures for duration of about 10sec. The grain was removed from the motor after firing and was weighed to determine the mass consumption rate, which may be computed by the difference of the weight before and after firing. The fuel grain was cut along the length at four different points for visual inspection and measurement of the unburned thickness along the length of the fuel grain at 10mm intervals. The local regression rate was determined by measuring the unburned web thickness at each 10mm interval with the help of a micrometer (least count 0.01mm), assuming a steady and constant regression rate of fuel for the duration of combustion.

RESULTS AND DISCUSSIONS

In the present investigation fuel grains were subjected to regression at three different gaseous oxygen injection pressures, viz 7.17ksc, 12.14ksc, 21.09ksc, and nitrous oxide oxidizer at 16.87ksc injection pressure respectively. All the test firings were done for an average duration of about 10 seconds. The primary determined variables in the test were the regression rate, fuel consumption rate, oxidizer mass flow rate and total mass flux.

Figure-2 shows the local regression rates for three different gaseous oxygen injection pressures. It has been found that the nature of variation of local regression rate along the length varies with oxidizer injection pressure. At low injection pressure (7.17ksc), the local regression rate after decreasing from the maximum at the leading edge attains more or less constant value in most of the part of the grain except at the end of the grain where again it shows a increasing trend. The deviation of local regression rate from the average value is within ± 0.14 mm/sec. As the injection pressure increased, the regression rate at the



leading edge increases drastically. At 12.14ksc injection pressure, it decreases up to a certain length of grain and then maintains more or less constant value till end of the grain whereas at 21.09ksc injection pressure, the regression rate droops steeply from the maximum at the leading edge, remains constant in the middle portion of the grain and again increases steeply towards the end of the grain. This trend of variation in regression may be due to surface combustion in addition to gas phase combustion in the initial portion of the fuel grain thus resulting in higher regression rate in this region. The high regression rate at higher injection pressure or towards nozzle side of the grain may be due to the increasingly higher mass flow rate along the length of the grain.

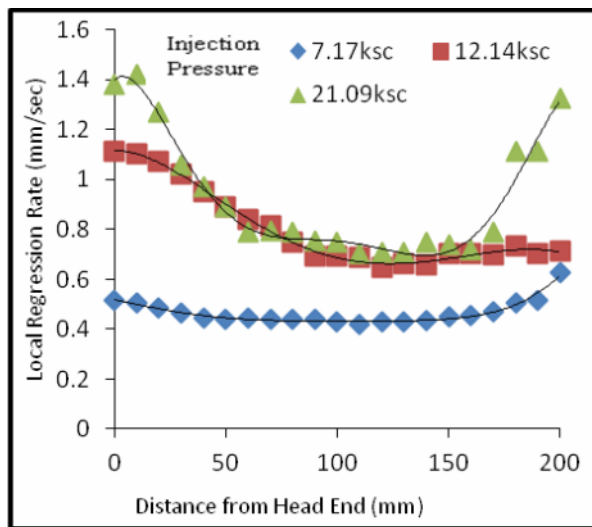


Figure-2. Local regression rate of paraffin wax burning with gaseous oxygen.

Figure-3 shows the average regression rate of paraffin wax hybrid fuel in all the cases which was determined by averaging the local regression rate at all locations where measurements were made assuming a constant regression rate during the short duration of test firing. The average regression rate has been found to increase with injection pressure. Increase of injection pressures, increases the oxidizer mass flow rate for a fixed injector configuration on the one hand and enhances the chamber pressure for fixed nozzle geometry on the other hand. Both the parameters i.e., oxidizer mass flow and chamber pressure are regression rate enhancers. Figure-4 shows the variation of average mass consumption rate with oxidizer injection pressure. A linear relationship has been observed in the present investigation.

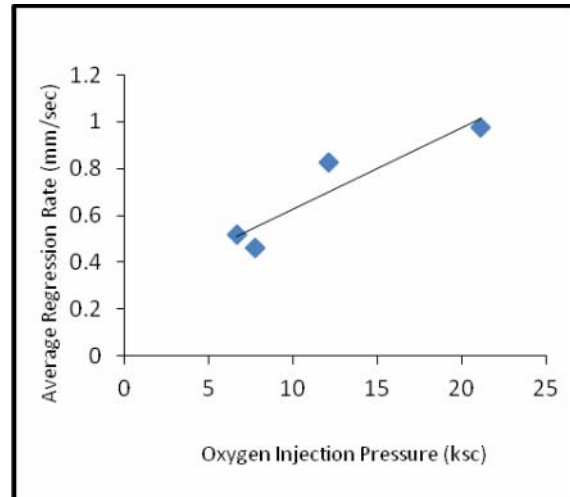


Figure-3. Average regression rate of paraffin wax burning with gaseous oxygen at different injection pressures.

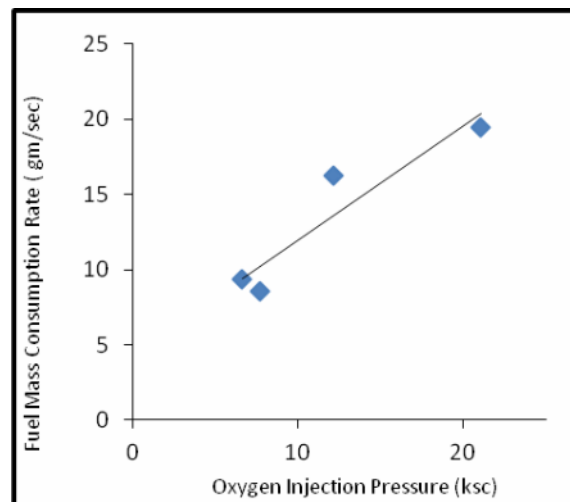


Figure-4. Effect of injection pressure on mass consumption rate of fuel, burning with gaseous oxygen.

The total mass flux has been observed to increase along the length of the paraffin wax fuel grain as shown in the Figure-5. This may be attributed to the injection of gaseous oxidizer in a constricted port area, resulting in impingement on the fuel surface. As more and more fuel was introduced into the combustion gas stream, the total mass flux values increased. That's why towards the nozzle end, the total mass flux tend to move up. From the Figure-5, it has been observed that total mass flux increases with increase in oxidizer mass flow rate. As the mass flow rate of oxidizer is higher, more amount of oxidizer tends to react with the paraffin fuel during the combustion process, which results in higher total mass flow rate.

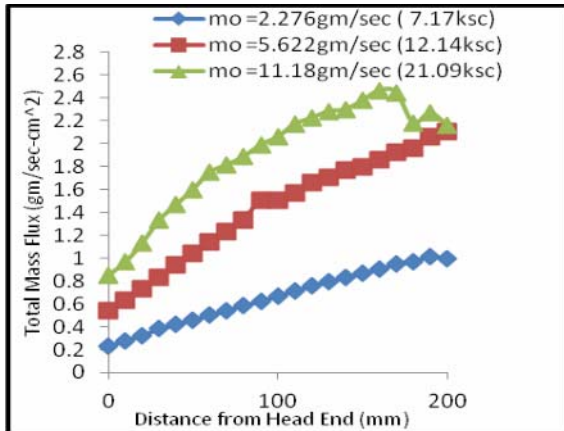


Figure-5. Total mass flux of paraffin wax burning in the stream of gaseous oxygen at different oxygen injection pressures.

The local regression rate of wax-oxygen and wax-nitrous oxide system are compared and presented in Figure-6. It is observed that wax-oxygen system gives higher local regression rate, higher average regression rate and higher mass consumption rate in comparison to wax-nitrous oxide system. The results are as per expectation. Under the similar oxidizer injection condition, the mass flux of oxidizing species present in gaseous oxygen are much higher when compared to oxidizing species available due to decomposition of nitrous oxide. Higher mass flux of oxidizing species is bound to give higher burning rate because the combustion goes closer to stoichiometric combustion.

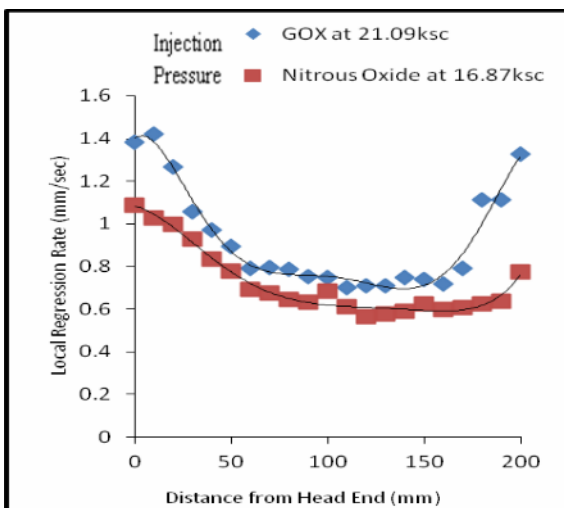


Figure-6. Comparison of local regression rates of paraffin wax burning with GOX and NOX.

Visual observations as well as photographic video recordings have also been made during the static tests of paraffin wax hybrid fuel grain in the stream of gaseous oxygen and nitrous oxide and some of them have been presented in Figure-7, Figure-8 and Figure-9. Bright

intense flame was observed at 7.17ksc and 12.14ksc oxygen injection pressure whereas at 21.09ksc oxygen injection pressure, the flame appearance was intermittent and highly smoky. This may be due to high flow velocity within the port which drags away liquid wax from the surface resulting in highly fuel rich mixture in the combustion zone. Another reason for such highly smoky flame may be due to the lack of sufficient residue time for combustion mixture within the combustion chamber to react completely thus resulting in incomplete or partial combustion. Nitrous Oxide/Paraffin wax hybrid system firing was done at 16.87ksc injection pressure for 12.47seconds. During the initial stage of the firing, it was observed that the fuel oxidizer mixture did not reach its ignition point and an intermittent flame was observed and this condition persisted well into the middle stages of the firing duration. Appearance of the flame can be seen in Figures 10 and 11. Only at the end of the firing, a continuous flame was observed for about 4 second's duration. During the initial stages, chuffing instabilities seemed to dominate the combustion process.



Figure-7. GOX injection pressure 7.17ksc.



Figure-8. GOX injection pressure 12.14ksc.



Figure-9. GOX injection pressure 21.09ksc.



Figure-10. Nitrous oxide injection pressure 16.87ksc (After 4 seconds).

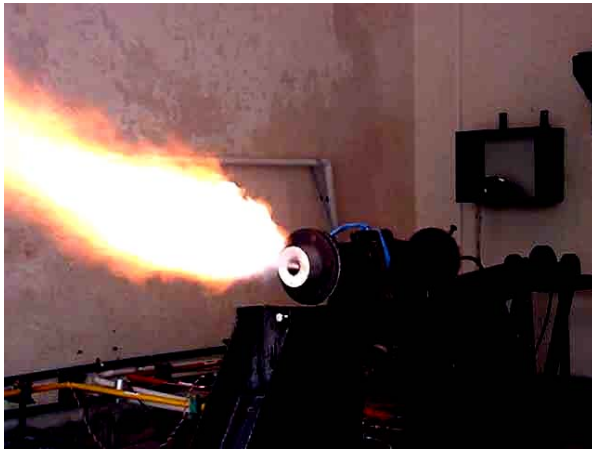


Figure-11. Nitrous oxide injection pressure 16.87ksc (After 9 seconds).

CONCLUSIONS

The regression rate of paraffin wax fuel burning in the stream of gaseous oxygen has been found maximum at the head end of the grain, it decrease up to a certain distance and remains more or less same except towards the nozzle end where again it show a increasing trend. The average regression rates of paraffin wax were found increasing with increase in oxidizer injection pressure. The average regression rate of paraffin wax was found lower value with nitrous oxide oxidizer as compared to gaseous oxygen. The appearance of flame towards the end of firing with nitrous oxide suggests further modification of firing unit including injector and igniter. The local regression rate values of nitrous oxide oxidizer were found less fluctuation when compared to gaseous oxygen oxidizer.

ACKNOWLEDGEMENTS

The authors are grateful to the Department of Space Engineering and Rocketry, Birla Institute of Technology for providing necessary assistance to carry out

this research work. They are also grateful to all faculty for their help.

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