THE PERFORMANCE OF A HYBRID ROCKET WITH SWIRLING GOx INJECTION

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Introduction

Hybrid rockets possess several safety and operational characteristics that provide attractive advantages over current solid propellant and liquid bi-propellant systems. In contrast to solid propellant grains, pure solid fuel grains are insensitive to cracks and imperfections and safe to manufacture, store, transport and launch. Hybrid rockets can also be throttled for thrust tailoring, shutdown, restart and incorporate non-destructive mission abort mode. Also, since the fuel is stored in the form of a solid grain, classical hybrid rockets require only half the feed system hardware of liquid bi-propellant engines, providing a simpler, more flexible design with improved reliability. Due to these safety and operational advantages, classical hybrid engines should be more economical to manufacture and launch than current propulsion system.

Classical hybrid rockets have not yet found however, widespread use for either commercial or military applications, possibly because they suffer from slow solid-fuel regression rates, low volumetric loading, and relatively poor combustion efficiency. To achieve the necessary mass flow rate of pyrolyzed vapor from the fuel grain to produce the desired thrust level, complex cross sectional geometries with large wetted surface are must be employed. Such grains require large cases and display poor volumetric efficiency. Low regression rates are also disadvantage when small L/D ratios may be desirable, such as for upper stages.

The complete modeling of hybrid motor combustion is quite complicated due to various physical and chemical processes. The model has to consider in a fuel grain passage a reacting flow created by the two distinctly different fluids: one, the mostly-vaporized-oxidizer entering the fore end of the fuel grain passage and the other, the fuel vapor blowing from the passage-wall. The boundary layer growing from the fore end of the passage contains the diffusion flame front within. Fuel is vaporized as a result of heat transferred from the flame front to the fuel surface. The fuel vapor converts towards the flame front while the oxidizer from the free stream diffuses into the boundary also towards the flame front from the opposite direction. Furthermore, at motor operating conditions characterized by high Reynolds number a finite flux of unreacted oxidizer to the fuel wall could exist through the mechanism of bulk turbulent eddy transport across the flame. The flame front is established at a location within the boundary layer determined by the stoichiometric conditions under which combustion can occur. The thickness of the flame is determined by the reaction rate at which the oxidation can occur. This rate is mainly dependent on pressure and typically follows an Arrhenius relationship. However, this is unimportant for the location of the flame front as diffusion rate is lower than reaction rate. The primary mechanism of heat transfer to the fuel surface is by convection and radiation. There is a strong coupling between the convective heat transfer and the rate of fuel vaporization. (“blowing” rate) since the blowing decrease the convective heat transfer to the fuel surface. There is also indirect coupling between the convective and radiative heat transfers because the latter tends to increase the blowing rate, which in turn tends to decrease the convective heat transfer. At the fore end of the grain the free

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Abstract

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stream consists of pure oxidizer at a low temperature. Along the fuel grain passage the oxidizer concentration decreases and the temperature increases. With the two zones on either side of the flame front, vitiated by the combustion products, the combustion, through stoichiometric, is occurring drawing the increasingly diluted oxidizer and fuel-vapor along the grain. Since the oxidizer concentration reduces along the passage, the diffusion flame within the boundary layer moves away from the fuel surface. In the limit, if all available oxidizer consumed at a location along the grain passage, theoretically no flame can exist downstream of this location. However, the heat transfer to the fuel surface will continue from the hot combustion products causing the continuance of fuel vaporization. In the absence of any combustion downstream of the location, the blowing fuel vapor will only cool the passage flow.

In 1960s, many researchers realized that the fuel regression rate is the key parameter affects the performance of a hybrid rocket. Many regression rate formulas have been published to explain the combustion phenomena inside the hybrid rocket chamber. Among them, a well known formula for HTPB regression rate expressed as function of oxygen mass flux , $r = 0.034GOx^{0.681}$ (mm/s) [1], has been employed widely for 1-D case. Philmon et. al [2] presented $r = 0.077GOx^{0.53}$ for cylindrical grain (length/port diameter at 400/20mm value) application. In order to study the fuel regression rate enhancement, Philmon et.al investigate the effects of the addition of ammonium perchlorate (AP) or aluminum in the fuel. The experimentally obtained the fuel regression rate increased remarkably by adding additives. Knuth et.al [3] designed a vortex hybrid engine having the capability of generating coaxial, co-swirling, counter flowing vortex combustion field and obtained fuel regression rates up to 650% larger than those in similar classical hybrids.

With the developed HTPB curing process[4], a 10-Kg thrust hybrid rocket was built and passed several static firing tests here in ASTRC. The motor was designed similar to the classical one with an aft-mixing chamber[5]. The purpose of preset study is then to develop the enhancement mechanism for oxidizer and fuel vapor mixing and flame holding to assess the necessity of aft-mixing chamber that is usually employed in a classical hybrid rocket design.

Experimental Set-Up

Fuel Grain Specimen. The solid fuel composition was mainly of HTPB. The bond of NCO from isophorone diisocyanate, IPDI, which will react with OH from HTPB to cure the fuel. The fuel grain was prepared by mixing HTPB and IPDI with ratio of 92 to 8 for 20 minutes. The mixture was poured into a nitrite rubber tube of 2 mm thick that fixed in the cylindrical mode. The fuel grain was then placed in a vacuum bowl equipped with a vacuum pump to evacuee the vapor bubble generated during the grain preparing process. The mixture was cured for 3 days at 75C. The length, outer and port diameter of the grain were 179 mm, 38 mm and 22 mm, respectively. The fuel grain was bonded on the combustion case by using DC-3145 RTV before testing. The characteristic of pure HTPB combustion was estimated by employing C_4H_6 combustion simulation. Figure1 shows the adiabatic flame temperature from CEC-76 code under the 1 atmosphere and isentropic condition.

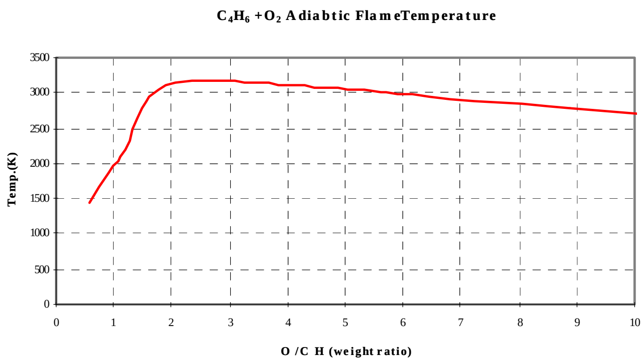

Fig. 1. $C_4H_6+O_2$ Adiabatic Flame Temperature.

Test Facility. The hybrid rocket test facility consists of GOx supply, N_2 purge, pyrogen ignition and thrust measuring systems. GOx is supplied from bank oxygen bottles kept at maximum pressure of 15 MPa. A pneumatic control ball valve located at thrust stand is used to initiate and terminate the oxygen flow. A Venturi sonic nozzle is placed in the line to measure and maintain a desired constant mass flow rate. The pressure upstream the sonic nozzle is always kept high enough to maintain the choked condition at the Venturi. Oxygen supply to the motor is through two hanged flexible Teflon hoses. Nitrogen is employed as purge gas to terminate combustion after the desired burning time. Propane gas and a spark formed the pyrogen igniter to initiate the test. Hybrid rocket thrust is measured by a flexure plate type thrust stand, in which hanged horses design and placed pneumatic control devices on the stand are employed as shown in Fig. 2. The natural frequency of the thrust stand measured is 8Hz. The length of 190 mm hybrid combustion chamber is a thick steel cylinder with inner diameter of 44 mm Schematic of the test motor is shown in Fig. 3. Zirconium base material is used for rocket nozzle. The erosion rate on the radius was around 0.07mm/s. in the case of test time of 6 sec and GOx mass flux of 100 $kg/m^2/s$.

Fig. 2. Thrust Stand.

GOx can enter the combustion chamber with or without swirling. For the non-swirling case, GOx is guided into a 12 mm circular channel and then directed to the port section of the grain. Therefore, a similar dump combustor is formed providing a stable combustion environment. For the swirling inlet, 12 tangential inlets on the circumference of the swirl inner case provide the swirling GOx injection capability. Each inlet has diameter of 2 mm hole and makes angle of 55 with motor axis. This annular swirler is then characterized as strong swirl one with swirl number of 0.95. The axial location of these inlets is designed so that the axes of all inlets will intersected at center point of the grain front surface.

Experimental Procedure. The oxygen regulator located at upstream of the sonic Venturi was first be adjusted to the desired value to supply a constant oxygen mass flow rate during test. The pyrogen igniter and test motor was then purged by nitrogen gas. The pyrogen igniter was initiated and maintained for 2 seconds. Immediately after turning off

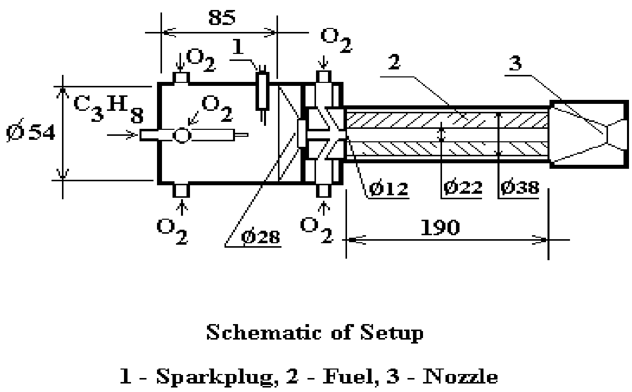

Fig. 3. Test Motor Configuration.

the ignition system, the pneumatic control valve was actuated to supply the oxygen. After the desired burn time, in quick successions oxygen supply was cut off and nitrogen purge was opened to extinguish combustion. The test measurements were the thrust and pressure at upstream and downstream of sonic Venturi and at aft chamber. All of the signals from stain-gauge type, pressure transducers and oxygen temperature were recorded by LabView system including PCI-6024E, SC-2345 and SCC-A113 interface cards. The sampling rate was 10 samples/s. The other pre-and post- test measurements were the fuel density, the initial and final nozzle throat diameters and grain mass and dimension. For each test, the desired oxygen mass flow rate could be obtained by choosing an appropriate Venturi nozzle throat and its upstream pressure.

Result and discussion

Hybrid rocket combustion can be characterized as diffusion flame that is mainly controlled by the degree of the mixing of oxidizer and vaporized fuel. The flame front is established at a location within the boundary layer determined by the stoichiometric conditions under which combustion can occur. The more chance provided for mixing, the better combustion performance of a hybrid motor would be. To enhance the mixing and flame holding capability, the idea of providing re-circulation zone in the fuel grain passage is employed in the present study. GOx passage of 12 mm diameter is guided into the port diameter of 22mm of the fuel grain, thus formed a sudden expansion combustor which has been proven as an excellent flame holder. Gox with swirling injection can also further provide a better mixing and flame holding for a diffusion flame combustion system. Both the effects of sudden expansion combustion and swirling Gox injection on the performance of a 10 kg thrust hybrid rocket engine are investigated in this study

Effects of re-circulation zone in the passage. A wider nozzle plume is observed as shown in Fig. 4 for the test of passage without re-circulation zone. Same diameter of GOx passage and the initial port diameter forms non-recalculation opportunity and thus, poor mixing. Heavy soot accumulated was observed on the post-test nozzle. This indicates the incomplete combustion inside motor. It is believed that poor mixing might

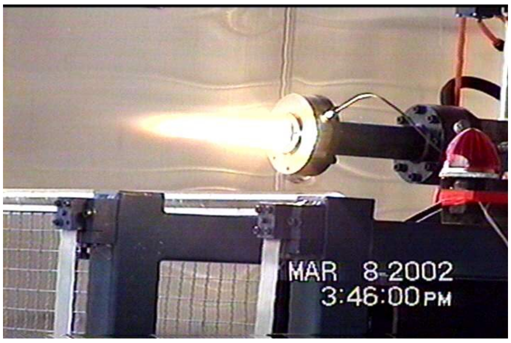

Fig. 4.Exhaust Plume (Non-recirculation) (030804).

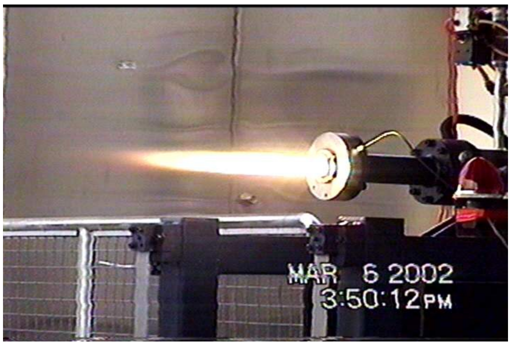

Fig. 5. Exhaust Plume (Recirculation) (GOx=90.87,030601).

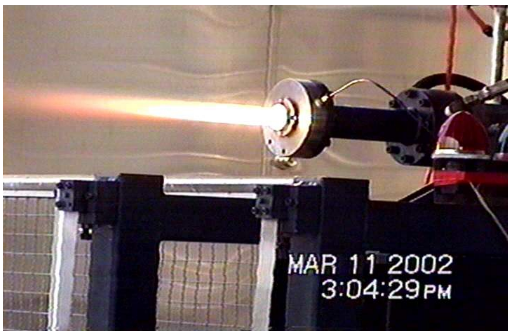

Fig. 6. Exhaust Plume (Swirling injection) (GOx=85.99,031103).

caused part combustion occurred outside nozzle. Figure 5 shows a little better plume shape for the non-swirling GOx injection but with recalculation zone inside grain passage (similar plume configuration was observed for a motor equipped with aft-mixing chamber but without recirculation zone design). In contrast to non-swirling case, Fig. 6 shows a long and bright plume observed for swirling GOx injection condition. Most of the classical head-end injected hybrid motor equipped with an aft-mixing chamber located at aft end of the fuel grain to provide a better chance for mixing and flame holding. The defect of this extra dead weight might be solved by a proper flame holder design.

Fuel regression rate. Grain contour at preset burning time can be measured by employing combustion termination technique. Figure 7 shows the longitudinal variation of burnt web thickness which is interpolated to t = 1 sec for comparison. As expect, the higher GOx mass flux supplying the better chance for oxygen reacting with fuel vapor, higher burnt web thickness is, therefore obtained. It seems a uniform burning rate along the axis was maintained during the test. A little bit lower regression rate near fore end of the fuel grain as indicated in the figure is probably caused by the recirculation zone, in which week convective transport exists.

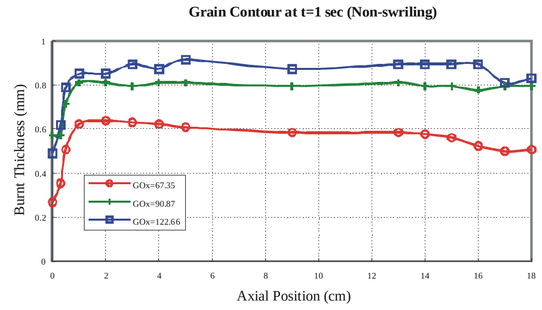

Fig. 7. Grain Contour at t= 1sec (Non-swirling).

Rugged grain surface distribution along the axis is shown in Fig. 8 for swirling GOx injection case. The higher regression rate observed near fore end of the fuel grain is believed caused by high swirl shear that might tear pyrolyzed fuel into combustion zone. The non-uniform distribution of the grain surface indicates violent mixing between oxidizer and fuel vapor.

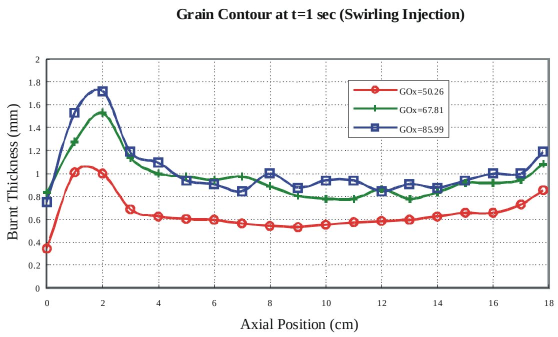

Fig. 8. Grain Contour at t= 1sec (Swirling).

Fuel regression rate is estimated mainly by weight method that the grain weight burnt is employed as the base for regression rate calculation. The regression rate is assumed to be a constant providing a constant GOx supplying. Oxygen mass flux is obtained based on the average port area and action time that has been widely used in rocket engine. As compare with data of reference [2] the present test results show lower regression rates because of lower L/D being used in the study as indicated in Fig. 9. The well-known regression rate form 1-D model [1] shows, as expect, lower than the present results. Swirling GOx injection results about 50%

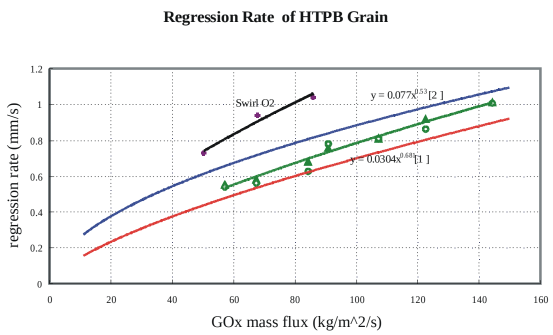

Fig. 9. HTPB Grain Regression Rate.

regression rate increase as shown in the figure. Estimation of the HTPB fuel regression rate is also conformed by grain contour measurement, in which the average of the grain thickness burnt was used for calculation. The symbol of "+"shown in Fig. 9 represents the regression rate obtained by the contour measurement which presents a good agreement with that by weight method.

Effects of swirling GOx injection. Swirling GOx injection will enhance the fuel regression rate and the mixing mechanism between oxidizer and fuel vapor. Figure 10 shows about 30 % increase in Isp (specific impulse) is obtained as compare to non-swirling one. Rocket motor thrust and chamber pressure are also obtained higher than that of S = 0 case. The weight ratio of oxidizer and fuel flow rate provides another information for improving the design of a hybrid rocket. Not all oxidizer are well mixed and reacted with fuel vapor as shown in Fig. 11 for the non-swirling case, in which combustion was in fuel –lean condition. Isp only increases slowly with GOx increase. With Swirling GOx injection, a better performance hybrid rocket can be obtained with less GOx supply as shown in the figure. To provide a better mechanism for oxidizer and fuel mixing is an important issue need be considered for developing a high performance hybrid rocket system

Motor re-start test. The re-start capability was performed in this study. Figure 12 shows the pressure and thrust profiles. The fuel was ignited at 1.5 sec and burnt for 5 sec, follow that the oxygen valve was closed. The thrust and chamber pressure then began to drop as combustion ceased. After a short off time of 1.5 sec, the motor was re-started by opening the oxygen valve. The burn time for the second portion of the test was 6 sec. The oxygen flow was 16.7g/s for both segments of the test. Re-ignition was achieved by simply flowing oxygen into the combustion chamber. It appears that the fuel surface remained hot enough during the shutdown interval to re-establish combustion. No other ignition source was required. Note that the pressure and thrust traces rise rapidly back to their previous levels after restart, indicating a rapid ignition.

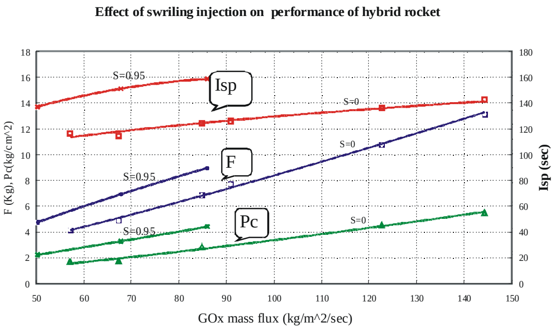

Fig. 10. Effect of Swirling GOx Injection on Performace of a Hybrid Rocket Engine.

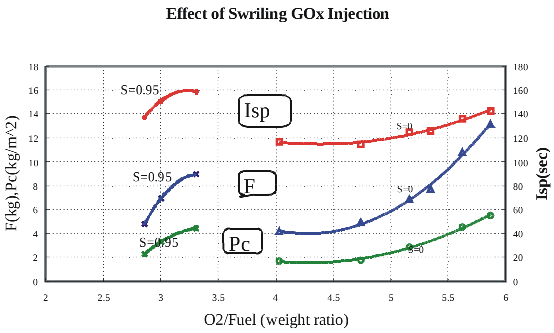

Fig. 11. Effect of Swirling GOx Injection on O/F Ration.

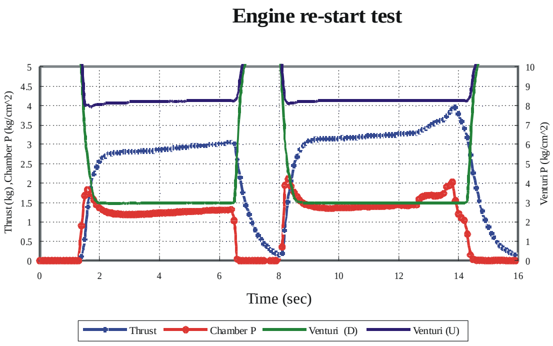

Fig. 12. Hybrid Rocket Engine Re-start Test..

Conclusions

With the developed HTPB curing process, a 10-Kg thrust hybrid rocket was built and passed several static firing tests. The motor was designed to have the capability of providing recirculation zone in the flow passage and swirling GOx injection for studying the effects of mixing enhancement mechanism on the performance of a hybrid rocket engine. Several conclusions are listed as follows.

1. A wider nozzle plume was observed for burning a motor with non aft-mixing chamber and re-circulation zone in the flow passage. Heavy soot accumulated on the convergent section of the nozzle was also observed.
2. A long and bright plume observed for burning a motor with dump combustor geometry and swirling GOx injection indicates nearly complete combustion occurred inside motor.
3. Fuel regression rate is estimated by both weight grain contour measurement method. The test results shows lower than that of Philmon 's data [2] because of lower L/D being used in the study. Swirling GOx injection results about 50% regression rate increase as compare to non-swirling one.
4. Motor with swirling GOx injection performs about 30 % increases in Isp (specific impulse) as compare to non-swirling case. Rocket motor thrust and chamber pressure are also increased accordingly. As compare to fuel lean combustion occurred in non-swirling condition, swirling GOx injection provides the opportunity that motor could be operated near stoichiometric condition.
5. A nearly complete combustion observed in the exhaust plume indicates that the classical aft-mixing chamber design becomes extra for a motor with swirling GOx injection
6. The re-start capability was performed after a short off time of 1.5 sec. No other ignition source was required. The rapid rising pressure and thrust traces shows that the present hybrid rocket has rapid re-ignition property

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