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Testing of Paraffin-based Hybrid Rocket Fuel using Gaseous Oxygen Oxidiser

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ABSTRACT

A series of paraffin-based hybrid rocket fuel has been studied experimentally in a laboratory-scale motor. To enhance the regression rate of paraffin solid fuel, three types of grain configurations: Cylindrical, star, and helical grain configurations of paraffin wax have been developed and tested with gaseous oxygen. The helical fuel grain presented best performance among all the test ports. About 40.2 per cent and 20.6 per cent regression rates are increased by burning paraffin fuel with helical and star grain configuration respectively, as compared to cylindrical grain configuration at G_{ox}=0.0191 g/mm^{2}s. The regression rates were significantly influenced by the oxygen injection pressure varied between 344.7 kPa and 620.5 kPa. Furthermore, the experimentally obtained exponents of oxidizer mass flux for all three grain configurations have been found to be significantly different from those of the classical hybrid system. Finally, thrust-time traces for all three grain configurations were also studied. The result shown no significant increase or decrease in the amplitude of the thrust oscillations.

Keyword: Hybrid rocket, regression rate, injection pressure, helical grain, star grain

NOMENCLATURE

$\dot{r}$	Regression rate (mm/s)
G	Total mass flux (g/mm^{2}s)
G_{ox}	Gaseous oxidiser (g/mm^{2}s)
m_f	Fuel mass flow rate (g/s)

1. INTRODUCTION

Hybrid rocket propulsion is attractive for its potential safety, non-polluting, and low-cost characteristics as compared to solid rocket. In addition, the ability to change thrust over a wider range, engine shutdown and restart can be easily obtained by controlling oxidiser flow through the hybrid rocket motor. Other advantages offered by hybrids over liquid rockets include lower temperature sensitivity and throttling ability. A regression rate measurement in hybrid rocket engine is pre-requisite for the motor design. However, classical hybrid rockets have suffered from slow solid-fuel regression rates. Thus most of the researches are focused on the subject to enhance the regression rate of solid fuel without sacrifice the efficiency. Due to low regression rate of rubber-based hybrid rocket solid fuel the attainable thrust level is very low as compared to other chemical rockets. Several investigations have been reported from researchers to enhance the regression rate of solid fuel. Some of the methods are use of energetic metallic additives in fuel, swirl oxidiser injection as well as insert in the port of fuel grain to enhance the turbulence level prior to combustion. Hence, some of conventional hybrid motor has designed with multi-port grain configuration to achieve the required thrust levels. However, these conventional methods also have undesirable characteristics.

Fast burning paraffin-based solid hybrid fuel was developed and tested at Stanford University[1]. The results reported enhancement of regression rates 3-4 times larger than the conventional solid fuels. Since, the high regression rate attributed to the entrainment of liquid droplets of paraffin into the flame zone leads to a more dominant mass transfer mechanism.

Carmicino and Sorge[2] conducted a series of firing test to investigate the influence of the oxidiser injection on the solid fuel regression rate behaviour. The regression rate of solid fuel was observed to increase several times in the region of the oxygen impingement on the grain's surface. The ultrasound pulse-echo technique was used to measure local instantaneous regression rates. George[3], *et al.* carried out systematic experimental investigations for regression rate enhancement for HTPB/G_{OX} system. The effects of addition of Ammonium Perchlorate (AP) or Aluminium in the solid fuel, the variation of oxidiser fuel ratio, and the variation of characteristic dimensions of fuel grain had been reported. While the addition of AP/A*l* and reduction of the grain port diameter enhances the regression rate. Experimentally obtained exponents of oxidiser mass flux and port diameter were found to be significantly different from those of the conventional turbulent diffusion-limited theory.

Experimental studies on combustion characteristics of cylindrical multi-port grain of a 96 mm diameter hybrid rocket motor were conducted by Kim[4], *et al.* This work brought out the effect of the port number and the distance between ports on a regression rate of solid fuel. The results indicate that the regression rates become fast as the port number increases to a typical number up to 4 ports. Series of experiments were conducted to investigate the enhancement of regression rate with a helical grain configuration and embedded metal wires

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in solid fuel. Test results reported[5] that the embedded metal wire's method turned out to be ineffective, whereas 50 per cent enhancement of regression rate was observed with helical grain configuration.

Changjin[6], *et al.* conducted a series of experimental investigation to optimise the conditions of oxidiser swirl flow and grain configuration for enhancement of regression rate of solid fuel. PMMA with gaseous oxygen was the solid fuel for investigation. The test results also revealed that, with helical grain configuration the regression rate enhanced up to 50 per cent. Also, numerical simulations showed that a helical grain induces swirl flow and increase the turbulence level along the helical grain. The ignition of the paraffin/polyethylene as solid fuel, regression rates and burning performance with gaseous oxygen were studied by Santos[7], *et al*. The main conclusion of their work was that the regression rate of paraffin-based fuel enhanced two to three folds compared to the ultra-high molecular weight polyethylene.

Smoot and Price[8] carried out the large number of slab burner test to characterize the regression rate of butyl rubber, polyurethane, and L.H/butyl rubber systems. Pressure dependence was found to be greatest at high flow rates, where as regression rates were found to be nearly independent of partial pressure at the lowest flow rate domain. Their correlation predicted that the experimental regression rates to be within ± 40 per cent. To extend the residence time of oxidiser in fuel grain port Wilkinson[9], *et al.* used a taper fuel-grain cavity in the hybrid motor. Results of static test firing showed an improvement in specific impulse of 10 per cent with useful increment in regression rate. It was also observed that the increased regression rate not up to the level as compared to the work of other using gaseous oxygen.

This paper details the regression rate finding of solid fuel with different grain port geometry. The fuel and oxidiser selected for the experimental investigation are paraffin-wax and gaseous oxygen respectively.

2. EXPERIMENTAL SETUP

2.1 Fuel Grain Specimen

In the present experimental investigation four types of paraffin fuel port configuration were considered. The first three circular, star and helical grain configurations were developed. The second circular fuel grain consists of 85 per cent paraffin and 15 per cent *Al* by mass as additive. The grain length for all three types of configuration was kept 88 mm. The port diameter for circular grain configuration was 10 mm whereas for the star and helical grain configurations the diameters were 10 mm (OD), 8.89 mm respectively. Detail of all the three grain is summarized in Table 1 and Fig. 1. The fuel grains were

Table 1. Summary of grain geometry

Grain configuration	Grain length (mm)	Port diameter (mm)	Port area (mm^2)	Initial grain mass (gm)
Cylindrical	88	10	78.53	440
Star	88	10(OD)	58.88	445
Helical	88	8.89	62.13	465

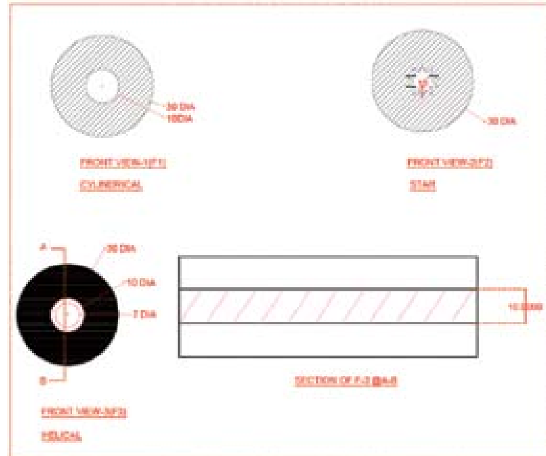

Figure 1. Solid fuel grain configuration.

prepared by pouring liquid paraffin wax into casing block with centre spindle of diameter 10 mm. The paraffin has a tendency to shrink in volume when transitioning from liquid to solid. Hence, the fuel grain after casting was allowed to cool and re-solidify very slowly at room temperature to avoid this issue. The casted paraffin fuel grains were observed free from any bubbles or major cracks along the length of grain. The pre and post firing test results were shown in Fig. 2. The *Al* metal loaded paraffin fuel grain was tested (tearing by hand), significant strength and uniform distribution of aluminium particle was observed throughout the fuel grain.

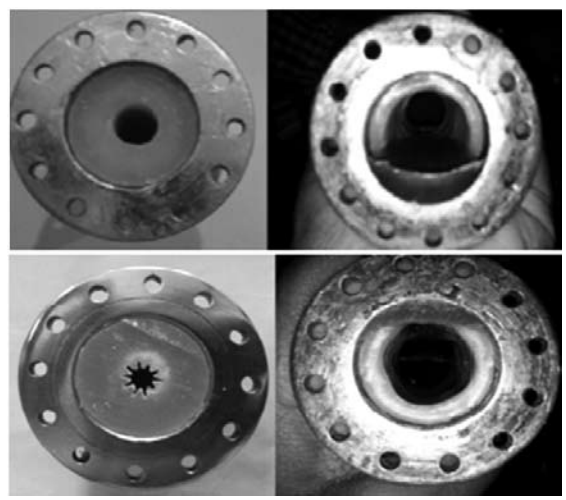

Figure 2. Pre- and post-test result for cylindrical and star paraffin fuel grains.

2.2 Test Equipment

The hybrid rocket test facility consists of G_{ox}, hybrid motor, ignition system and thrust measuring system. Gaseous oxidiser system was designed to supply and to regulate the flow of oxygen from cylinder into the motor during test. A pressure regulator was used to control and to maintain the desired constant mass flow rate of oxygen. Two NRV valves were included in the supply line to prevent the back flow into oxygen cylinder. High pressure oxygen Teflon line was used as a feed line from oxygen supply. The oxygen supply was guided into inlet of injector plate through a cup shaped oxidiser chamber of length 33 mm and diameter 30 mm. Injector plate of stainless steel with 47 mm pitch circle diameter was used to ensure axial injection of oxidiser. Injector plate consists of 17 number of holes with diameter of 1 mm. The length of hybrid rocket motor combustion chamber was 92 mm with inner diameter 30 mm. Schematic of test motor as shown in Fig. 3. A straight cone convergent-divergent nozzle was used with throat diameter 6 mm and nozzle area ratio 7.

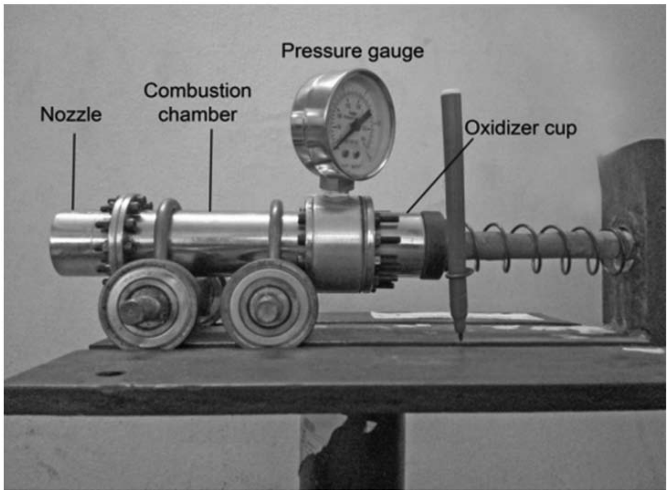

Figure 3. Schematic of hybrid test motor.

2.3 Thrust Measurement

The thrust was measured using calibrated-spring mounted on the head end of hybrid test motor. The test motor was mounted on bearing, which can accommodate linear and rotary motions simultaneously, used for the free motion of the hybrid rocket motor on the slots of test stand. During the test firing, the thrust force exerted by motor on spring was proportional to its deflection.

Thrust detector was calibrated using Hook's law. Known loads between 1 kg and 6 kg were suspended from the spring testing machine and the deflection of spring was collected. The stiffness of the spring was 1 kg/mm. The calibration curve is shown in Fig. 4.

2.4 Experimental Procedure

The fuel grain of required size was loaded in the combustion chamber at a distance of 2 mm from the head end. The combustion chamber wall surface was inhibited with inhibitor and cured grain was bonded to the inhibitor using epoxy resin. To conduct each test run and to maintain consistency during the test a set of general procedure was followed. The oxidiser injection pressure was regulated at the desired value with the help of a regulator. After the flow became steady in oxidiser chamber, the combustion was initiated by a pyrogen igniter. The igniter was placed at the port of the fuel grain towards the head end of the grain already loaded in the combustion chamber.

Oxygen gas was injected as soon as the igniter fired and the combustion was terminated after a lapse of pre-requisite duration by cutting off the oxidiser flow. The test measurements were the thrust and the chamber pressure. The other pre-and post-test measurements were the oxygen mass flow rate and final fuel grain weight. A test firing of hybrid motor with helical fuel grain was shown in Fig. 5.

3. RESULT AND DISCUSSION

The regression rate of hybrid fuel plays an important role in the satisfactory design and development of practical hybrid propulsion system. The combustion in hybrid rocket motor for paraffin-based solid fuels is significantly different than that for classical rubber based fuel. The combustion process can be characterized as heat is transferred through convection and radiation from flame zone to the fuel. Due to entrainment of small droplets from liquid layer on the fuel surface to combustion zone cause dominant mass transfer mechanism and cause the fuel to burn much faster. This new process of mass transfer is attributed to low melting point of paraffin. To enhance the regression rate of paraffin solid fuel, three types of grain configurations are employed in the present study.

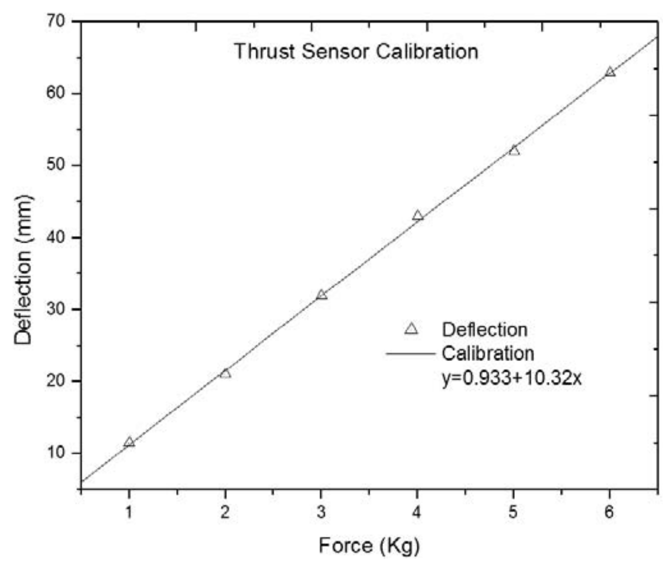

Figure 4. Calibration of the thrust sensors.

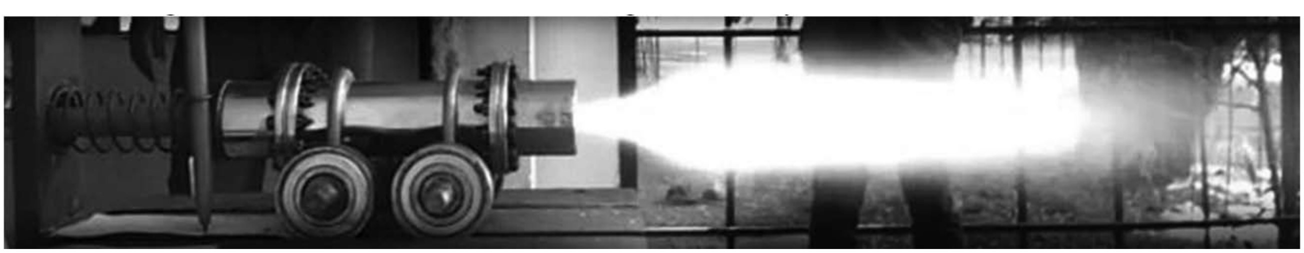

Figure 5. Test firing of hybrid motor with helical fuel grain.

Table 2. Summary of lab-scale hybrid test firings

Grain configuration	Oxygen injection pressure (kPa)	Chamber pressure* (kPa)	Burning time (s)	Oxidizer mass flux G_{ox} (g/m²s)	Regression rate (mm/s)	Oxidizer flow rate (g/mm²s)	Thrust (kgf)
Cylindrical	344.7	448.1	6.48	0.0191	2.76	1.50	0.2
Cylindrical	413.6	503.31	10.64	0.0371	4.00	2.92	0.3
Cylindrical	482.6	586.0	9.22	0.0364	4.36	2.86	1.0
Cylindrical	551.5	689.4	5.11	0.0509	4.76	4.00	1.2
Cylindrical	620.5	827.3	4.16	0.0713	6.08	5.60	1.9
Star	344.7	427.4	6.48	0.0354	3.71	2.08	0.5
Star	413.6	537.7	7.39	0.0435	4.20	2.56	1.0
Star	482.6	565.3	9.22	0.0714	4.75	4.20	1.8
Star	551.5	723.9	5.11	0.0905	5.21	5.32	2.5
Helical	344.7	448.1	6.48	0.0445	4.62	2.77	0.8
Helical	482.6	641.2	9.22	0.0548	4.72	3.41	2.0
Helical	551.5	758.4	5.11	0.0879	4.96	5.47	2.8
15 per cent *Al* mixed with paraffin wax	344.7	517.1	6.48	0.0231	3.65	1.82	1.0

* Chamber pressure recorded after the combustion initiated. (The combustion chamber pressure was recorded when the burning surface area was at the maximum. The increased chamber pressure as compared to oxidiser injection pressure was attributed to increased temperature after burning of the solid fuel.)

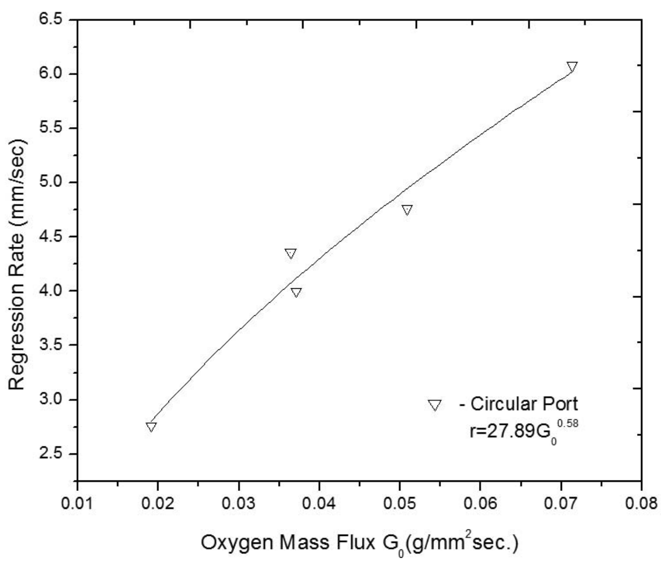

Figure 6. Regression rate variation for cylindrical grain with oxidizer mass flux.

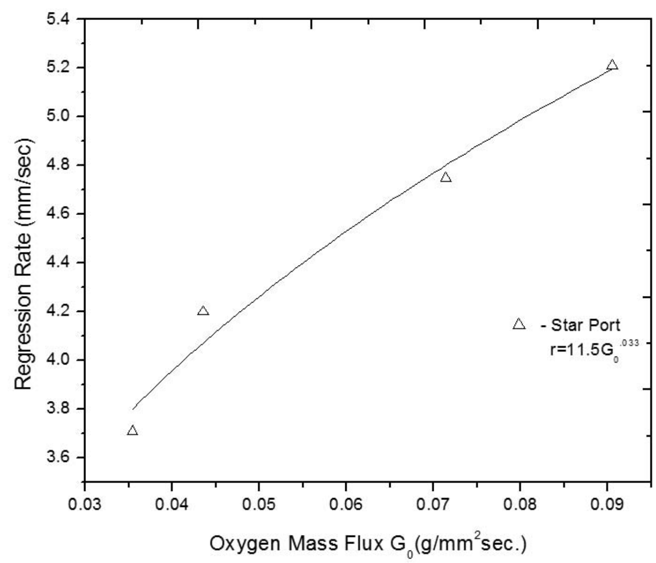

Figure 7. Regression rate variation for star grain with oxidizer mass flux.

3.1 Fuel Regression Rate

Static test firings are carried out with circular, star and helical fuel grain configurations. The oxidiser injection pressure varies between 344.7 kPa and 620.5 kPa. Regression rate is determined mainly by the grain weight burnt during the test. Oxygen mass flux is estimated based on the average port area. The experimental results have been presented for all the test firing in Table 2. Figure 6 through Fig. 8 show the regression rate variation with Oxygen mass flux for circular, star and helical port configuration respectively. A curve fit to the regression rate data point results in an oxygen mass flux exponents of 0.58, 0.33 and 0.11 for cylindrical, star and helical port configuration respectively. It has been observed that this value is slightly smaller than the flux exponents commonly observed in classical hybrid rocket fuel. Since, the fuel regression rate is the exponential function of oxidiser mass flux. So, the higher oxygen mass flux in Fig. 7 resulted in the higher fuel regression rate and much fuel from surface was vaporized toward the diffused oxidiser in combustion zone.

As compare with all three ports configuration the result shown lower regression rates for circular port because of the change of flow characteristics in each fuel port as indicated in Fig. 9. The result shown enhancement of turbulence by helical grain is one of the important design factors in controlling

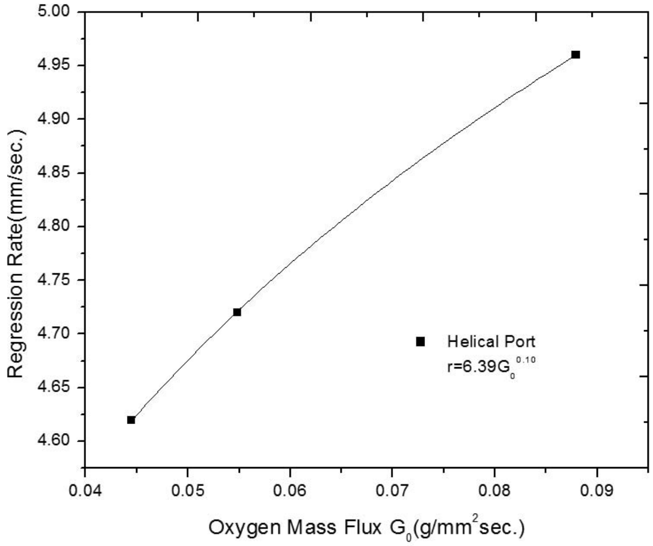

Figure 8. Regression rate variation for helical grain with oxidiser mass flux.

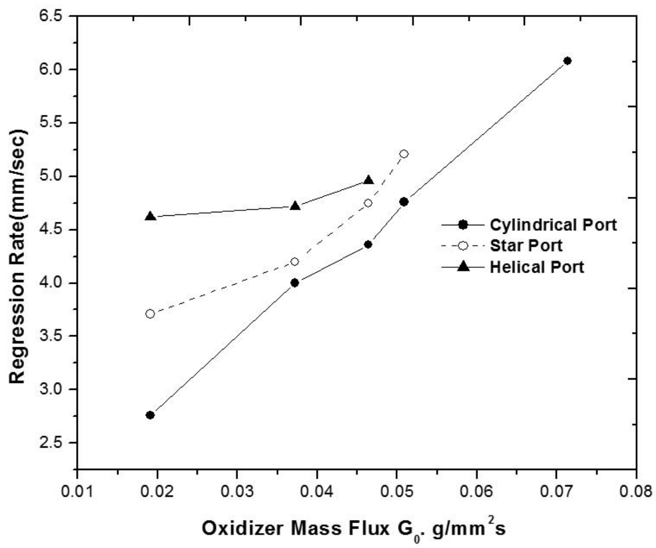

Figure 9. Effect of different grain configuration on regression rate of fuel.

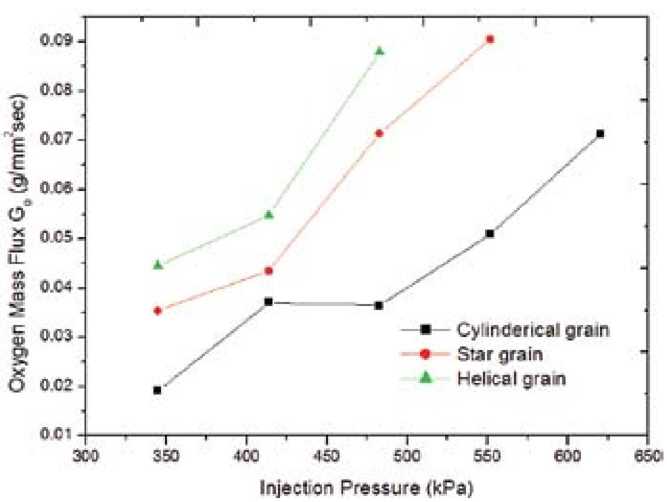

Figure 10. Effect of G_{ox} injection pressure on regression rate.

the regression rate along with the residence time of oxidiser stream.

3.2 Effect of Oxidiser Injection Pressure

Oxygen injection pressure was varied using the oxygen regulator ahead of injector. Fig. 10 illustrates the increasing relationship between oxygen injection pressure and fuel mass flow rate. The enhanced fuel liberation rate associated with helical port among all three port configuration due to the increasing oxygen injection pressure. The tailored regression rate of helical port is attributed to generation of turbulence by the interaction of helical groove over the fuel surface with the axial flow. This turbulence effect could enhance the convective heat transfer and produce excessive burning of the solid fuel, although the star port showed higher regression rate as compared to cylindrical port.

3.3 Thrust-time Profile

The thrust-time traces of entire three port configuration generally showed the characteristics of classical hybrid rockets. According to the values at Fig. 11, the case with 15 per cent *Al* additive in fuel produced about 1 kg thrust and chamber pressure at 517.1 kPa, the other star and helical port are 0.5 kg, 0.8 kg thrust respectively. The star grain showed a neutral burning thrust-time profile whereas cylindrical and helical grain indicated progressive burning. For further comparison, test was also conducted at oxygen injection pressure of 482.6 kPa and 551.5 kPa. It was also observed from Fig. 12 that the motor thrust for cylindrical grain at 482.6 kPa injection pressure tailored to 1kg whereas star and helical grain shown increment of 1.8 kg and 2 kg respectively. Thrust-time profile for 551.5 kPa injection pressure was also shown in Fig. 13, thrust for star and helical grain configuration tailored to 2.5 kg, 2.8 kg respectively. However, the thrust-time profile remains unchanged as compared to 344.7 kPa and 482.6 kPa of oxygen injection pressure.

The thrust for all three grain geometries as a function of oxidiser mass flux are plotted in Fig. 14. The standard deviation gives a measure of the amplitude of the oscillations during the

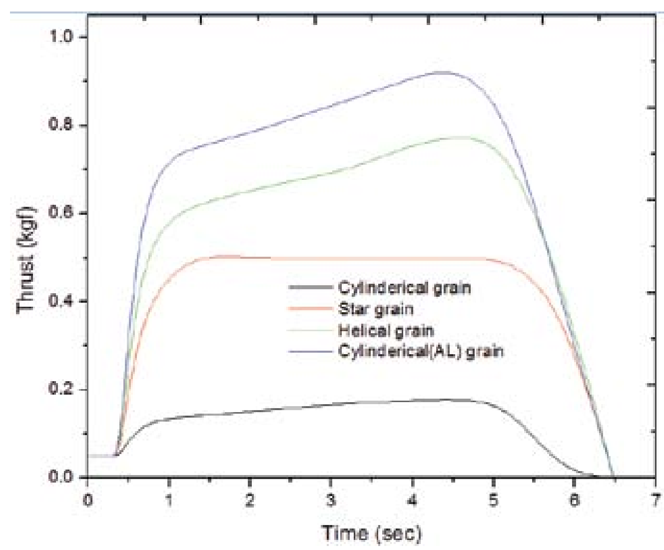

Figure 11. Thrust-time traces for 344.7 kPa.

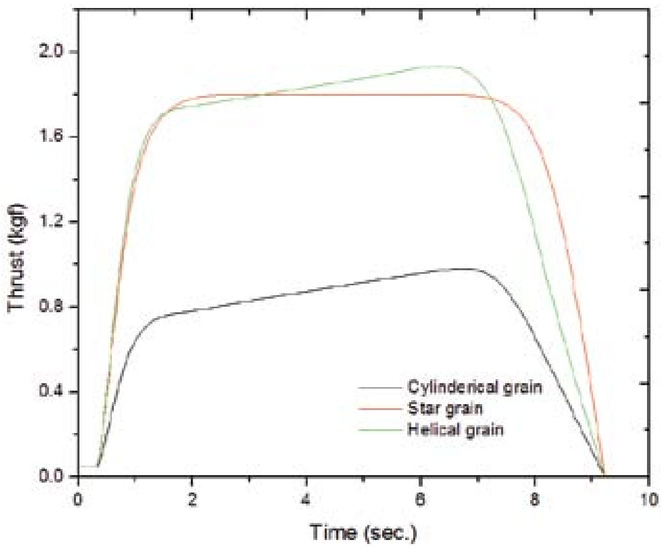

Figure 12. Thrust-time traces for 482.6 kPa.

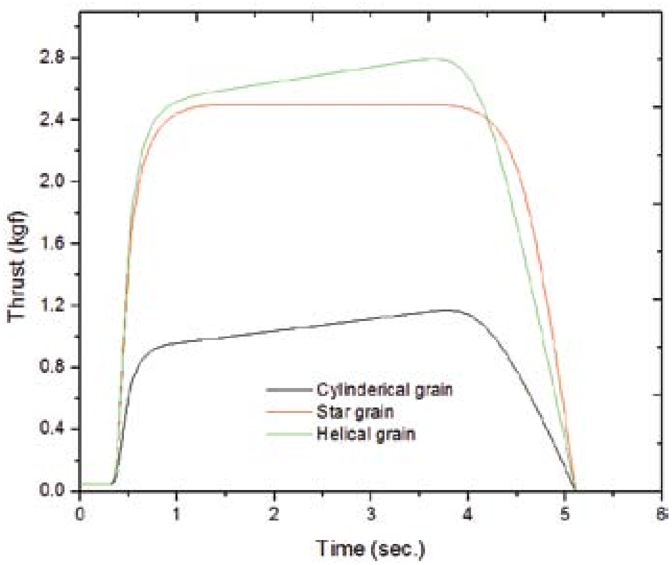

Figure 13. Thrust-time traces for 551.5 kPa.

motor operation. Higher the standard deviation in thrust data indicate large the amplitude of pressure oscillation. Table 3 shows the average thrust and standard deviation for several different oxygen mass fluxes.

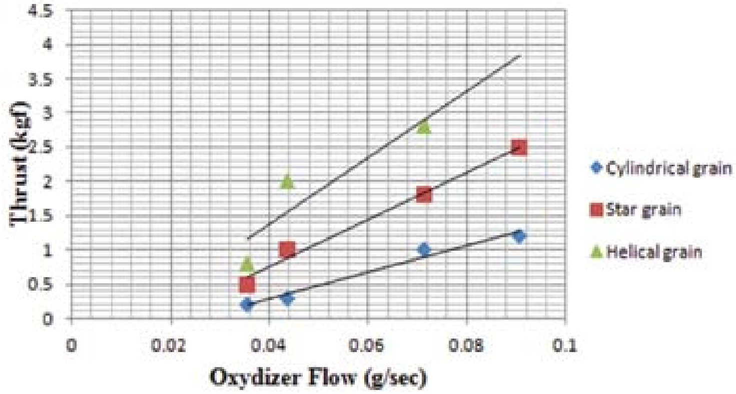

Figure 14. Effect of oxygen flow on thrust for various grain geometries.

Table 3. Average thrust and standard deviations for several G_{ox} mass flux

Grain configu-ration	Oxygen mass flux (g/mm²s)	Average thrust (Kgf)	Std dev
Star	0.0354	0.5	3.2
	0.0435	1.1	7.4
	0.0714	1.86	12.6
	0.0905	1.85	12.4
Cylindrical	0.0191	0.2	0.13
	0.0371	0.3	0.19
	0.0364	1	0.68
	0.0509	1.2	0.81
	0.0713	1.9	1.3
Helical	0.0445	0.8	0.54
	0.0548	2.0	1.4
	0.0879	2.8	1.9

4. CONCLUSIONS

A series of paraffin-based hybrid rocket fuel have been studied experimentally in a laboratory-scale motor. To enhance the regression rate of solid fuel, different grain configurations are studied. The main conclusions that can be drawn from this work are listed below:

- Hybrid propulsion system is easy to operate in static tests.
- Enhancement of regression rate can be achieved by employing a suitable helical grain configuration.
- Star and helical grain configuration enhanced the fuel regression rate in Paraffin/G_{ox} hybrid motors as compared to cylindrical grain.
- Helical groove in fuel port significantly generated turbulence in the flow which enhanced the fuel regression rate.
- The present experimental results indicate that the exponents of the mass flux for cylindrical, star, and helical grains are 0.58, 0.33, and 0.11, which are significantly less than 0.8. Hence helical grain configuration reported low G_{ox} index.
- Thrust-time profile obtained with star grain is nearly constant for all the oxidiser injection pressure.
- Thrust-time traces have been studied for all three grain port configurations. The helical grain reported a highest thrust of 2.8 kg among all three port configuration.
- Standard deviation in thrust is independent of oxygen mass flux. Therefore, the amplitude of oscillations is not a factor of oxidiser mass flux. Since different fuel port configurations showed an increase in regression rate and thrust, and not increase the amplitude of thrust oscillations.

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