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COMBUSTION PERFORMANCE OF HYBRID ROCKET MOTOR UNDER THE INFLUENCE OF CYLINDRICAL PROTRUSION

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The sequence of hybrid rocket motor static firings is performed with and without cylindrical protrusion, to evaluate the combustion behavior of Bee wax fuel grain. Firing is done for the injection pressures of 2.75bar, 4.15bar, and 5.51bar respectively, all firings are done for an identical firing duration of 7 seconds. Experimental outcome confirms an addition cylindrical protrusion as vortex generator yield an average of 45% higher regression rate than that of the baseline rocket motor. Among all injection pressures, modest 4.15 bar with cylindrical protrusion shows the significant improvement in the combustion performance by exhibiting the enhanced regression rate as well as mass consumption rate the fuel grain. Hence, the addition of cylindrical protrusion as a vortex generator to the classical hybrid motor promise to improve the combustion performance of the bee-wax fuel grain.

***Keywords*:** Hybrid rocket, Regression rate, Vortex generator, Bee-wax fuel grain.

1. Introduction

Propulsion systems which play the major role as a workhorse for the space launch vehicles to accomplish its mission. Different rocket engines are used in the launch vehicles based on its mission requirements. Currently, solid, liquid and cryogenic engines are employed to perform the mission task. Among these engines, solid and liquid engines are widely used in primary stages of the launch vehicles. Even though, these engines are used primarily both engines has some characteristics, which need to be addressed to optimize the vehicle performance. The hybrid rocket is naturally safer than other rocket engines, where the oxidizer is stored as a liquid and the fuel as a solid. Hybrid rocket motors are less susceptible to chemical explosion than conventional solid and bi-propellant liquid designs[1]. The main shortcoming of the hybrid is that the combustion process relies on a relatively slow mechanism for combustion, with a sequence of fuel melting, evaporation, and diffusive mixing. But, in a solid rocket, the flame is much closer to the fuel surface and the regression rate is typically an order of magnitude larger. As a rough comparison, the regression rate in a classical hybrid rocket fuel regression rate is typically one-third of the composite solid rocket propellants[2].

In order to compensate for the low regression rate, the surface area for burning must be increased. This is accomplished through the use of a multi-port fuel grain, but it reduces the volumetric loading as well as structural integrity of the fuel grain[3]. More attempts are made to increase the regression rate by increasing the heat transfer rate to the fuel surface. Mainly, the performance of a hybrid motor depends critically on the degree of flow mixing attained in the combustion chamber, also the local regression rate of the fuel is quite sensitive to the general turbulence levels of the combustion port gas flow because localized combustion gas eddies or recirculation zone adjacent to the fuel surface act to significantly enhance the regression rate in this area [4]. In this work novel idea of using blunted object like cylindrical protrusion is employed to induce the turbulence in the combustion port, where the bee-wax fuel grain is selected to perform combustion analysis.

2. Experimental setup and Research methodology

The experimental setup consists of a Static Firing mount, a rocket motor assembly, solid fuel grain, oxygen supply, ignition setup, recording device, and hand tools. This section gives a detailed description of each and every component and subsystem of the complete setup. The hybrid rocket motor unit consists of the parts like an accumulator, combustion chamber, and nozzle. All the subcomponents are fabricated by stainless steel 304 grade. In general accumulator consists of an oxidizer settling chamber followed by the shower head injector plate with six orifices of diameter 1.5mm, subsequently, the combustion chamber is fabricated for the length to diameter ratio of 3. In case of the nozzle, the simple convergent-divergent cone shape is made from stainless steel with graphite insert for the throat diameter of 6 mm. A schematic of 3-D hybrid rocket motor is shown in the fig.1(a) & 1(b).

Fig 1(a) Exploded View

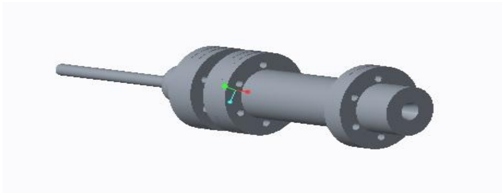

Fig 1(b) 3-D Assembled view

The primary aim of this work is to analyze the combustion behavior of bee-wax in the hybrid rocket motor with and without cylindrical protrusions. The first set of firing is carried out without the cylindrical protrusion for injection pressures of 2.75bar, 4.15bar, and 5.51bar, the second set of firing is also completed for the same injection pressures and firing duration with an attachment of cylindrical protrusion. In order to induce additional turbulence of the incoming gaseous oxygen, the blunted object like a cylindrical projection of 8mm is chosen as a vortex generator. Because it can generate larger wake region in the downstream, which can provide an additional turbulence fuel grain port[5].

A cylindrical projection is placed with a fixed distance of 50 mm from the injector plate also 25 mm ahead of the fuel grain. A specific CAD model of the vortex generator detail is shown in the fig.2(a).

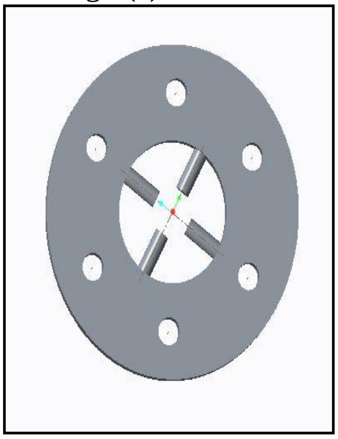

Fig 2(a). CAD model VG

Fig 2(b).Bee-Wax fuel grain and Wax quadrant

Gaseous oxygen along with the bee-wax is selected as a propellant combination for this experimental analysis. The bee-wax is received in the form of thick cubes, and then it is melted and molded using a cylindrical die to the configuration of single-port cylindrical shape. Once the molding is done the raw fuel grain is machined to give the length of 100 mm, outer diameter 45 mm, an inner diameter of 17mm respectively. A basic bee-wax molded fuel grin and wax-quadrant are shown in the fig. 2(b).

All the subsystems of rocket static firing unit like oxygen supply, an ignition device, recording devices are checked twice to ensure the reliability of each component. Similarly, a primitive examination of the parameters like throttling time, ignition pressure, cut-off timing was also carried out to ensure the safety of rocket firing. Based on the simulated firing inputs injection pressure is fixed between 2.75bar to 6.90bar. Similarly, firing duration is also fixed as 7seconds of its total firing duration in order to keep enough left out of fuel grain to complete combustion performance calculations.

The rocket motors combustion performance fully depends on the combustion parameters like local (i.e.: regression at any location along the fuel grain length) and average regression rate, the mass consumption rate of fuel etc. Regression rate is generally referred to as the burning surface of a propellant grain recedes in a direction essentially perpendicular to the surface, which is usually expressed in mm/s [6]. For further performance determination, the mass of the fuel grain before and after firing, and fuel grain web thickness before and after firing need to be measured and tabulated. After each firing rocket motor is allowed to cool for some time then the fuel grain is removed and sliced into four pieces as shown in the fig.5. From the injector end as a reference point length of 100 mm fuel grain is divided into 5 equal parts, from each locations local web thickness is measured using a screw gauge. Each static firing is recorded as a video with the help of a Nikon DSLR D5100 camera to evaluate the temporal behavior of rocket exhaust plume.

3. Results and discussion

In total six static firings are performed with and without the cylindrical protrusion, firings are conducted at the varied injection pressures of 2.75bar, 4.15bar, and 5.51bar for the fixed firing duration of 7 seconds. In order to evaluate the combustion performance of single cylindrical port fuel grain, the local & average regression rate, as well as mass consumption rate of fuel grain, are calculated from each rocket firing. likewise, each firing is recorded by the Nikon DSLR D5100 camera to measure the firing duration and to understand exhaust plume behavior fuel grain. Local regression rate behavior of bee-wax with and without cylindrical protrusions are given in fig 3.1.

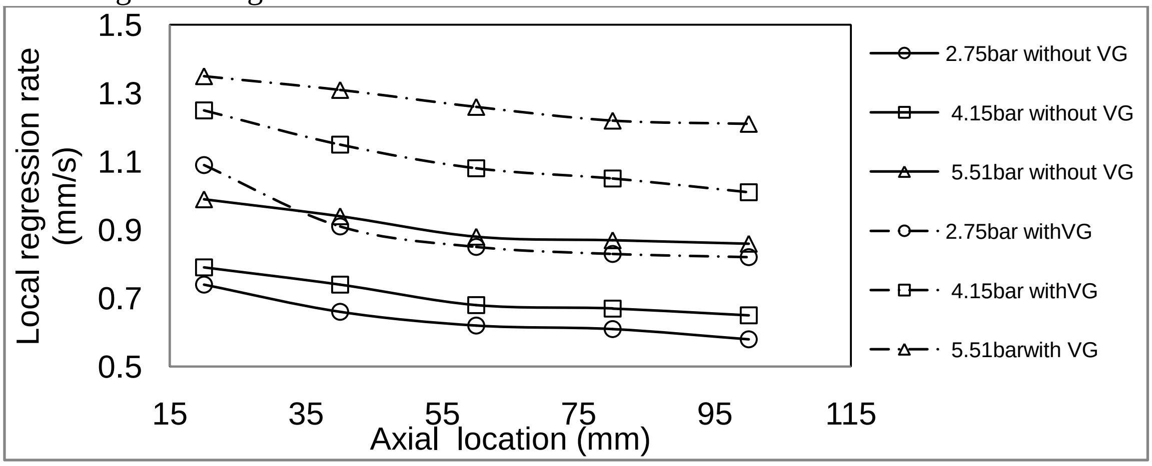

Fig 3.1: Local regression rates with and without VG

From the fig 3.1, each local regression rate curves of different injection pressures were distinguished into three regimes (1) high regressive head end, which is present near the injector surface. This end is susceptible to the maximum shear of the oxidizer flow (2) the mid-regressive end which occurs usually between $\left(\frac{1}{3} \leq l_c \leq \frac{2}{3}\right)$, where l_c is the total length of the cylindrical grain. In this regime, the grain experiences the high to mid level shearing[7] when axially measured towards the end (3) low regressive tail due to lesser shear than the other portion of the fuel grain, which is the end portion of the grain beyond which, the nozzle is located. Fig 3.1a, reveals that regression rate of the fuel grain increases linearly with oxidizer injection pressure, higher injection pressure leads to increase the amount of an oxidizer flux [1], hence amplified regression all along the fuel grain. Among the other injection pressures, the 5.51 bar of injection shows the higher local regression rate, because of higher injection pressure can get maxia mum mass flux of oxidizer into the combustion chamber. In case of firings without the VG, local regression value of fuel grain at the injector end varies between 0.75 mm/s to 1 mm/s for the base line firings(i.e.: without cylindrical protrusion) of all injection pressures.

As it can be noticed from the fig 3.1, the minimum injection pressure 2.75bar itself is reaching the local regression of 1.11 mm/s at an injector end, whereas maximum injection pressure of 5.51bar without VG reaches only 1 mm/s, which is roughly 11% higher. So, it is exceptionally apparent that fuel grain experiences an improved local regression all along fuel grain with the addition of VG. This enhanced regression is due to induced turbulence by the VG to the incoming oxidizer flow, this additional turbulence results in higher mixing & greater residual time[3]. As the injection pressures increase local regression profile attains more linear in nature. Interestingly, 4.15bar shows the superior improvement in the regression. This is mainly due to a higher percent of increment in the average regression rate (i.e.: 57%) as well as mass consumption rate (i.e.: 71%), as is can be seen from the table 3.2a & 3.2b respectively. Hence, the introduction cylindrical protrusion as VG seems to favors the moderate injection pressures like 4.15bar to possess a higher enhancement in the regression rate. Unlike baseline firings, rocket motor with VG gets higher regression values at the injector end ranges between 1.11 mm/s to 1.35 mm/s.

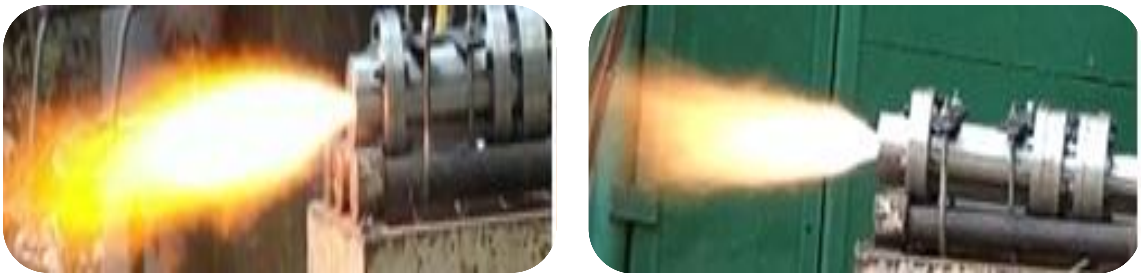

Fig 3.2: Exhaust plume of bee wax with and without VG at 60psi at t = 3s

Comparison of average regression rate and mass consumption rate of the grain for all the injection pressures with and without VG are calculated and tabulated in 3.3a & 3.3b. In the case of the average regression rate, fuel grain shows the average increase of 40%, 57%, and 39% for the injection pressures of 2.75bar, 4.15bar, and 5.51bar respectively. Similarly, fuel grain mass consumption rate also shows the significant improvement exhibiting average percent increase of 38%, 71%, and 21% for the injection pressures of 2.75bar, 4.15bar, and 5.51bar respectively. Higher local regression rate enhancement with VG at 4.15bar can be the main reason for this significant performance of the bee-wax fuel grain from the hybrid rocket motor. Finally, exhaust plume images of bee-wax are given in the fig.3.2, which shows the significant reduction in secondary burning area as well as plume length. This is due to effective mixing in the combustion port, because of induced turbulence from the cylindrical protrusion.

Table 3.3a: Average Regression rate of fuel grain with and without VG

Pressure (bar)	Average Regression rate of fuel grain (mm/s)		Increment %
	Without VG	With VG	
2.75	0.647	0.9083	40.38
4.15	0.709	1.1132	57.00
5.51	0.911	1.26876	39.27
Average increment			45.55

Table 3.3b: Fuel grain Mass consumption rate with and without VG

Pressure (bar)	Fuel grain Mass consumption rate (gm/s)		Increment %
	Without VG	With VG	
2.75	3.44	4.75	38.15
4.15	4.46	7.63	71.26
5.51	8.33	10.10	21.20
Average increment			43.54

4. Conclusion

This experimental work gives several insights on the enhancement of regression behavior bee-wax fuel grain in a Hybrid Rocket Motor under the influence of cylindrical protrusion. The rocket combustion performance parameters like regression rate and mass consumption rate are evaluated for the injection pressures of 2.75bar, 4.15bar, and 5.51bar respectively. The results obtained through this work shows that the inclusion of cylindrical protrusion as a vortex generator significantly improve the regression behavior of the bee-wax fuel grain for all injection pressure. Results obtained through the experiment are discussed thoroughly in the results and discussion section, only a few noteworthy points mentioned here which can be considered as a concluding point.

- Without VG the fuel grain experiences an average regression rate of 0.647 mm/sec at 2.75bar, 0.709 mm/sec at 4.15bar, 0.911 mm/sec at 5.51bar.

- Similarly with VG the fuel grain experiences the enhanced regression values like 0.90 mm/sec at 2.75bar, 1.11 mm/sec at 4.15bar, 1.27 mm/sec at 5.51bar.

- The percentage increment in local regression rates are recorded as 40.38% for 2.75bar, 57% for 4.15bar, 39.27% for 5.51bar. The average increment is around 45.55% overall.

- The percentage increment in mass consumption rate is recorded as 38.158% for 2.75bar, 71.268% for 4.15bar, 21.205% for 5.51bar. Average increment is around 43.54% overall.

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