

# Regression Rate Study of Cylindrical Stair Shaped Fuel Grain of Hybrid Rocket

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**ABSTRACT:** Hybrid rocket propulsion is a rising propulsion system which presents flashy features such as low cost, safety and environment friendliness. On the other side it has certain issues like mixture ratio shifting; low regression rates, mixing inefficiencies, and etc. bound its use as a prime propulsion system. The present analysis presents an approach for rectification of one of the most important among those issues, namely low fuel regression rate. By increasing oxidizer flow speed over the burning fuel surfaces the fuel regression rate can be increased. This is because flow over the burning surface creates shear stress which facilitates fuel and oxidizer mixing. One method of improving shear stress and thus regression rate is to induce an oxidizer vortex into the combustion chamber. The stepped fuel grain configuration is one of the mean. To create vortex combustion field in a port. To generate this flow, oxidizer is injected axially in the fuel grain and vortex created inside the grain due to different size of cylindrical port size. A series of static rocket firing were conducted to investigate the solid-fuel regression rate behaviour and operating characteristic of stepped solid fuel grain hybrid rocket motor. Results from eight tests of laboratory scale hybrid rocket motor using polyvinyl chloride and gaseous oxygen have been presented here at different oxidizer injections pressures i.e. 16.872, 21.092, 28.122, 42.184, and 48.511 (kgf/cm<sup>2</sup>) respectively. Higher regression rate has been observed in the case of cylindrical stair fuel grain compare to cylindrical grain

**KEYWORDS:** Fuel Grain, Regression Rate, Web Thickness, Mass Flow Rate, Injection Pressure, Fuel Flow Rate

## I. INTRODUCTION

Hybrid rocket propulsion system carries distinct advantages such as thrust flexibility, low environmental pollution, grain robustness, and propellant versatility over traditional solid and liquid rocket propulsion system shown in fig-1. Hybrid propulsion system is superior in many aspect compared to solid propulsion system or liquid propulsion system. Considering its merits, efforts has been given to develop a hybrid propulsion system in all over the world.

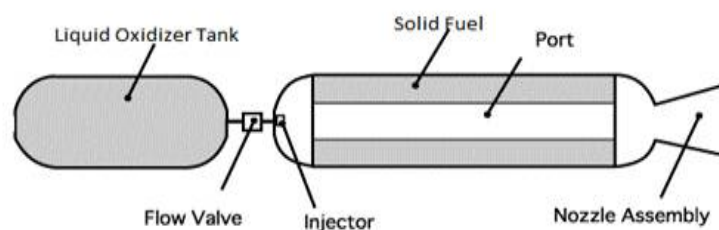


Fig – 1 Schematic Diagram of Hybrid Rocket Propulsion System

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A number of hybrid propellant combinations have been investigated to find a viable system and on the other hand a number of combustion models have been developed and a number of regression theories came out for efficient design and development of hybrid system. Owing to large number of advantages of stepped fuel grain over conventional hybrid fuel grain much attention has been paid to design a stepped fuel grain in order to increase the mass regression rate. A stepped grain is supposed to create circulation in the flow during the combustion inside the grain. Due to circulation in the flow vortices form and it will increase the surface erosion and also promote complete fuel oxidizer mixing. Various methods have been used to create vortex flow in cylindrical fuel grain including bidirectional injection of oxidizer, inlet swirl vanes, obstacle on the grain surface, obstacle in the flow field during combustion or aerodynamically – shaped swirled blades, vortex trippers, twisted tape inserts, propeller, coiled wire. Some of the important research and development work carried out last in fifty years in the area of hybrid rocket combustion has been presented below to highlight the progress as well as the present understanding of its characteristics. The combustion process in hybrid rocket was deeply investigated by earlier researchers. However, sufficient knowledge has been acquired to provide the basis for design of hybrid rocket fuel grain, full-scale engine and to achieve optimum combustion performance. The solid-fuel regression rate is a very important design and ballistic parameter in the study of hybrid rocket combustion.

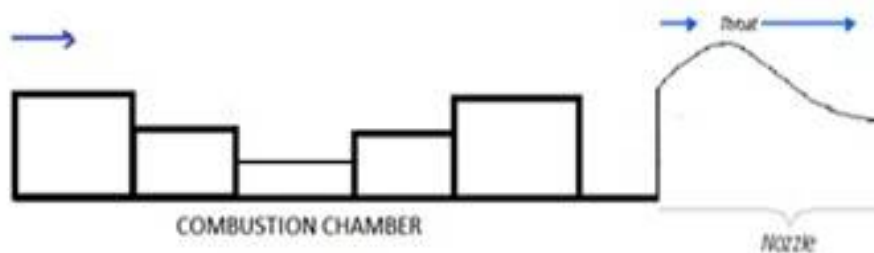


Fig – 2 Stair Shape Grain Inside Hybrid Rocket Motor

## II. RELATED WORK

The first analytical treatment of hybrid combustion was given by Bartel and Rannie [1]. They considered a model involving fuel in the form of a tube through which a one dimensional turbulent flow of air was considered. Marxman et al [2] developed a combustion model for the hybrid engine,  $G_{ox}=90\text{kg/m}^2\text{sec}$ . The combustion behavior of polymer based fuel (Plexiglas), in which the burning surface was a cylindrical hole, was investigated by Houser and Peck similar to that of a turbulent diffusion flame, where the flame zone was established within the system fuel entered the boundary layer as a result of the sublimation process at the wall, while the oxidizer was entered into the boundary layer from the main stream. Combustion occurs when a suitable mixture ratio was achieved. The fuel vapour converted towards the flame front while the oxidizer from the free stream diffused into the boundary layer. The mass flux was the key factor governed the regression rate of solid fuel.

$$(r' \propto G^{0.08})$$

Furthermore, the regression rate was a weak function of the axial distance.

$$(r' \propto X^{(-0.2)})$$

Pressure dependency was also influence the regression rate during the extremities of mass flux (i.e. very lower or very higher). Marxman et al [2] later attempted to modify Gilbert's original approach to account both for density variations and the blocking effects across the boundary layer to modify the exponent of B (i.e. 0.5 instead of 0.23). They predicted that the regression rate was a strong function of B. Estey et al [3] investigated that the including a radiant heat transfer term in regression rate equation to account for thermal radiation improved empirical correlations for metal-loaded fuels. However, the convective heat transfer theory worked best for pure hydro carbon fuels. Smoot and Price [4] carried out the large number of slab burner test to characterize the regression rate of butyl rubber, polyurethane, and L.H/ butyl rubber systems. They also studied the pressure dependence of hybrid fuel regression

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rates with oxidizer flow. Pressure dependence was found to be the greatest at high flow rates, whereas a regression rate was found to be nearly independent of partial pressure at the lowest flow rate domain. Their correlation predicted that the experimental regression rates to within  $\pm 40\%$ . The regression-rate model based on Liquid layer entrainment mechanism developed by Karabeyoglu et al [5]. They found that the fuel produced a very thin, low viscosity, low surface tension liquid layer on the fuel surface when it burnt; they observed that the regression rates was 3 to 4 times higher than the predicted classical regression rate. The mixture of 50% paraffin wax and 50% HTPB (so-called 50P fuel) presented the best performance among all test fuels studied by Lee [6]. About 185% and 105% regression rates was increased by burning with paraffin wax as compared to regression rates of HTPB swirling  $O_2$  hybrid system at [7]. Instantaneous burning rate were determined as a function of time, axial distance, and oxygen flow rate. Surface regression rate were predicted from the isothermal pyrolysis kinetic parameter of polymeric fuels and compared to the observed rates. The fuel regression rate in the most of hybrid rocket system is approximately 1.5mm/sec or less under motor-operating condition.

The basic problem that degrades the application of hybrid motors is the low regression rate of solid fuel. To overcome this problem in hybrid rocket many study carried out to increase the regression rate of solid fuel by changing the profile of regressing solid fuel grain. In the present study an effort has been made to investigate the local regression rate, average regression rate, effect of oxidizer injection pressure in the stream of  $GO_x$  for cylindrical stair shape fuel grain as show in fig-2

### III. RESEARCH METHDOLOGY

Hybrid rocket propulsion is a promising propulsion system which presents appealing features such as safety, low cost and environment friendliness. On the other hand certain issues like low regression rates, mixture ratio shifting, mixing inefficiencies, etc. restrict its use as a preferred propulsion system. The present investigation presents an approach for improvement of one of the most important among those issues, namely low fuel regression rate.

Fuel regression rate can be increased by increasing oxidizer flow speed over the burning fuel surfaces. This is because flow over the burning surface creates shear stress which facilitates fuel and oxidizer mixing. One method of improving shear stress and thus regression rate is to induce an oxidizer vortex into the combustion chamber.

The stepped fuel grain configuration is one of the mean. To create vortex combustion field in a por. To generate this flow, oxidizer is injected axially in the fuel grain and vortex created inside the grain due to different size of cylindrical port size. A series of static rocket firing were conducted to investigate the solid fuel regression rate behaviour and operating characteristic of stepped solid fuel grain hybrid rocket motor. Results from eight tests of laboratory scale hybrid rocket motor using polyvinyl chloride and gaseous oxygen have been presented here at different oxidizer injections pressures i.e. 16.872, 21.092, 28.122, 42.184, and 48.511 (kgf/cm<sup>2</sup>) respectively. To carry out the research programme as planned, the experimental works were done in the following area.

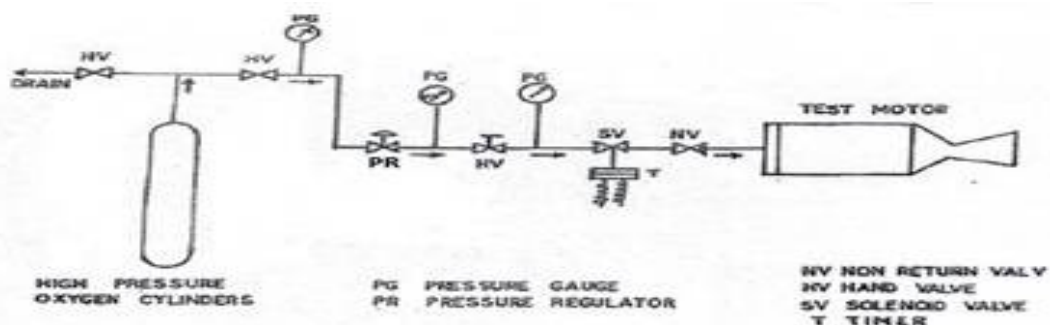


Fig – 3

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- Test Equipment

Test hybrid motor consists of oxidizer assembly, injector plate, and combustion chamber with solid fuel grain loaded and nozzle. Injector assembly consists of an injector plate of stainless steel with 168.5mm diameter, 10mm thick, with 10mm diameter holes and a cup shaped oxidizer chamber of length 66mm and diameter of 63mm. For swirl injector eight holes have been apart at 128 mm p.c.d., drilled at angle of with the axis to ensure Swirl type of injection. The gaseous oxygen feed system is used for test to carry out and feed system is composed of pressure regulator, check valve, and flexible Teflon hoses. The combustion chamber, of cylindrical shape, is provided with an outer-jacket for coolant passage. It is made of stainless steel of internal diameter of 90mm with length of 340mm. A straight cone convergent-divergent nozzle the total length of nozzle was 75.5mm, convergent side length was 33.15, divergent side length was 40.35 and the divergent angle was kept at. The exit diameter was 34mm; the maximum convergent side diameter was 77mm and the throat diameter 13.5mm. A nozzle retainer ring made of mild steel was used to hold nozzle with the combustion chamber having six equidistant holes of 14mm diameter at 128 mm. The fuel grain is directly cast into chamber and oxygen is injected into port of fuel grain. Fig.4 represents Section View of Hybrid Rocket Motor.

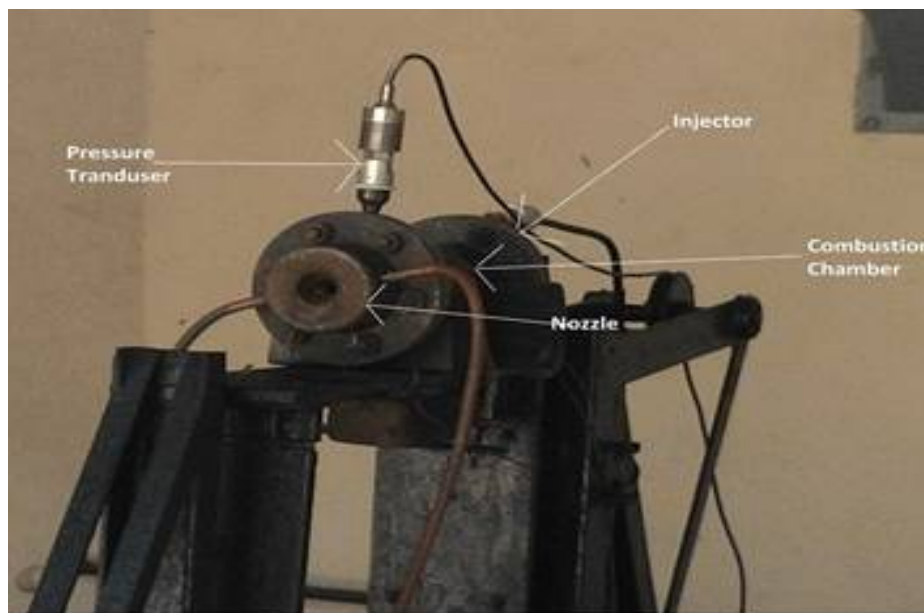


Fig – 4

- Fuel Grain Specimen

For present test, the composition of Polyvinyl Chloride (PVC) and Dibutylphthalate (DBP) were evaluated in each case and compared alone fuel grain. Commercial grade polyvinyl chloride and laboratory grade Di-butyl phthalate were used for preparation of fuel grains. PVC plastisol was chosen as fuel because of its good mechanical and chemical properties, processing ease, easily available and its wide applications in propellant industries both as fuel binder in solid propellant and as fuel in hybrid propellant. Di-butyl phthalate (DBP) was taken in a stainless steel beaker and heated it first fumes to remove the moisture. Then it was cooled down to room temperature. PVC was also dried at 550-600 for one hour to remove moisture. The required quantity of PVC and DBP were mixed thoroughly in a horizontal sigma blade mixer. The mixing was carried out for a period of 3hr to ensure uniformity in the fuel mixture. The mixing conditions were maintained uniform in all the mixing to ensure uniform mechanical properties. The fuel mixture was cast in aluminum mold having inside diameter 76mm and length 270mm and fitted with a mandrel. Three different diameter mandrals, 20mm, 25mm and 35 mm were used in present work to get the fuel

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grains of 20mm 25mm and 35mm port diameter. The top of the mold was closed with help of a push fit block. The provisions were made in the top and bottom enclosure to retain the mandrel at the center and the axial locations of the mold. Prior to filling process, the mold and mandrel were cleaned and coated with petroleum jelly to facilitate easy extraction of grain. The fuel mixture was cast in aluminium mold having inside diameter 76mm and length 270mm and fitted with a mandrel. Two different diameter mandrel i.e 20mm, 25mm and 35 mm were used in present work to get the fuel grains of 20mm, 25mm and 35mm port diameter. The top of the mold was closed with help of a push fit block. The provisions were made in the top and bottom enclosure to retain the mandrel at the center and the axial locations of the mold. Prior to filling process, the mold and mandrel were cleaned and coated with petroleum jelly to facilitate easy extraction of grain. The filled mold was cured at 1200C for 3 hours and after that kept at room temperature to cool down. The fuel grain was extracted from the mold manually, trimmed, checked for cracks and bubbles then it was stored in polythene bags to avoid contamination. To make cylindrical steeped grain, grains of two different inner diameters I.D = 41mm, 51 & 56mm and outer diameter 76mm of length 50 mm were joined alternatively by using araldite. These were later cast into the combustion chamber with the help of inhibitor made from PVC, DBP and Chalk Powder in the ratio of 2:2:3 respectively. The motor was kept in oven 1200C for an hour for curing the inhibitor and then it was allowed to cool down to ambient temperature.

#### • Igniter For Initiating the ignition

A pyrotechnic shellac igniter of the following composition was used to initiate the combustion in the rocket motor. I.

Shellac Powder: 20% by weight.

II. Hydrolyzed Shellac: 5% by weight.

III. Ammonium Perchlorate: 75% by weight.

IV. Ferric Oxide: 5gm per 100gms of igniter charge.

The primary igniter consisted of a bead of above composition around a three round coil of diameter 5 mm of Nicrome wire. The end of coil was soldered with long enameled copper wire for electrical connections. The secondary igniter was made with the beads of the above composition. The beads were sealed in a polythene bag. The primary igniter was inserted in it and the bag was tightly closed with the help of adhesive tape.

#### • Test procedure

The Igniter was placed at the head of the grain already loaded in the combustion chamber. The swirl injector was fitted at head end of the chamber with the help of nuts and bolts. The nozzle was fixed with the help of nozzle retaining ring. The test motor was mounted on the test bed rigidly and oxygen gas line was connected to the adaptor at the inlet of the oxidizer chamber. The water pipe was connected to the adaptors made in nozzle and water was circulated.

The oxidizer pressure was regulated at the desired value (i.e. 16.872kgf/cm<sup>2</sup> to 48.511kgf/cm<sup>2</sup> as mention in table-1 with help of a dome regulator and the combustion was initiated by switching on the ignition current. Oxygen gas was injected as soon as the 4129entim fired and the combustion was terminated after a lapse of pre-requisite duration by cutting off the oxidizer flow. The combustion of fuel grains were carried out for duration of 10 sec. The fuel grain were taken out of the combustion chamber after each test firing and were cut along the length at four points with the help of a sharp knife for visual inspection and measurement of the un-burnt web thickness along the length of the fuel grain. The fuel grain was weighed after firing to determine the mass consumption rate. The local regression rate was determined by measuring the un-burnt web thickness at each 4129entimetre interval with the help of a screw gauge. At each location, the web thickness has been determined at four points along the periphery and the average value has been taken to indicate the local regression rate at the station. The mass consumption rate was determined by the difference of weights before and after firings assuming a constant rate of consumption. The average regression rate was computed by averaging the local regression rate values using the average of the unburnt web thickness.

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## IV. EXPERIMENTAL RESULTS

In the present investigation, an attempt has been made to study the combustion characteristics of and PVC hybrid fuels. The local regression rate of uniform port cylindrical fuel grain is present in Fig-6 for different oxidizer injection pressure i.e 16.872, 28.122, 42.184 (kgf/cm<sup>2</sup>) respectively. It has been observed that the regression rate is maximum at the leading edge of the grain, than it decreases sharply with in a short distance, from the leading edge and after that it remains more or less same in the most of the length part except at the end of grain. The similar patterns of variation of local regression rate were found at all oxidizer injection pressure and the local regression rate of hybrid fuel grain is found to increase with increase in Oxidizer injection pressure.

By using swirl injector, direct impingement of oxygen at the inlet of fuel port results in high oxidizer concentration and heterogeneous chemical reaction due to that regression rate at the leading edge is more. Also, the flame zone is close to the grain port and hence the regression rate is obvious to be high at the head end. The oxidizer is depleted and reduced along the length of the solid fuel grain. On the other hand, the mass flux keeps increasing as we move forward. The regression rate at any location of the fuel grain may be taken to be dictated by two influencing parameters, namely quantity of oxygen at that particular location; enabling its diffusion in the flame zone in the sufficient quantity, and the total mass flux which is responsible for heat transfer to the fuel surface for pyrolysis. Regression rate is controlled by the heat transfer from flame to solid fuel surface. However, as the boundary layer grows along the grain length and flame zone moves away from the fuel surface. Hence the heat transfer from flame zone to fuel surface is decreased along the length and regression rate shows a decreasing trend. Before the nozzle end, regression increasing, this increase value of regression rate may be due to the excessive heating of the grain because of an accumulated high temperature combustion gases in the free space after the grain.

The local regression rates of cylindrical stair fuel grain for different oxidizer injection pressure i.e. 16.872, 21.092, 28.122, 42.184, and 48.511 (kgf/cm<sup>2</sup>) respectively. In this case the trend has been found similar to normal cylindrical grain as regression rate being highest at the head end but after that the uneven regression of grain surface was found till nozzle end. The higher port I.D of grain segment has lower regression rate compare to lesser port I.D grain segment. The similar patterns of variation of local regression rate were found at all oxidizer injection pressure and the local regression rate of hybrid fuel grain is found to increase with increase in oxidizer injection pressure.

Grain Configuration	Injection Pressure (kgf/cm <sup>2</sup> )	Chamber Pressure (kgf/cm <sup>2</sup> )	Avg. Regression Rate (mm/s)	Fuel Mass Flow Rate (gm/s)	Oxidizer Flow Rate (gm/s)	Total Mass Flow Rate (gm/s)
Cylindrically Stared Shape Grain	14.873	2.952	0.4628	15.35	49.84	66.19
Cylindrical	14.872	2.46	0.329	13.23	49.28	62.75
Cylindrically Stared Shape Grain	19.092	-	0.521	22.29	51.83	75.12
Cylindrical	26.122	7.03	0.478	24.48	60	85.48
Cylindrically Stared Shape Grain	26.122	8.436	0.6854	25.5	76.8	106.5
Cylindrical	40.184	-	0.495	26.52	70.315	97.835
Cylindrically Stared Shape Grain	40.184	9.983	0.79	29.24	103.56	135.17
Cylindrically Stared Shape Grain	46.511	10.827	0.84252	33.65	115.798	149.11

Table – 1

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Higher but uneven regression on the surface of stair fuel grain may be because of four parameters. Mainly due to stepping vortex flow field formation took place inside the port of the grain First the stepped grain configuration create vortex combustion field in the port. Which enhance the heat transfer to the regressing surface causes more uniform mixing of gas phase reactants. Ultimately it enhances the fuel burning rate. Second the vortex formation increases the mixing of the gas phase reaction. Third vortex flow increases the shear force on the surface of grain which also causes in enhancing the fuel regression rate. Fourth due to the oxidizer flow vortex tries to move towards the nozzle side therefore higher regression rate found on less port I.D of the grain.

### Average Regression Rate

The variation of average regression rate for both the grain configuration with different injection pressure has been presented in Fig-5 As expected of with increasing oxidizer injection pressure increase the average regression rate, because of increase in the oxidizer quantity for the combustion as well as due to high oxidizer injection pressure the oxidizer velocity is more which increase the shear force on the grain surface and causes increase in regression rate. In the present investigation similar results came out for both the grain configuration. We observe that the average regression rate is more in the case of stair grain configuration comparative to the normal cylindrical grain at particular the injection pressure. The result shows that the stepped grain configuration can be an alternative option in hybrid propulsion system to get higher regression rate.

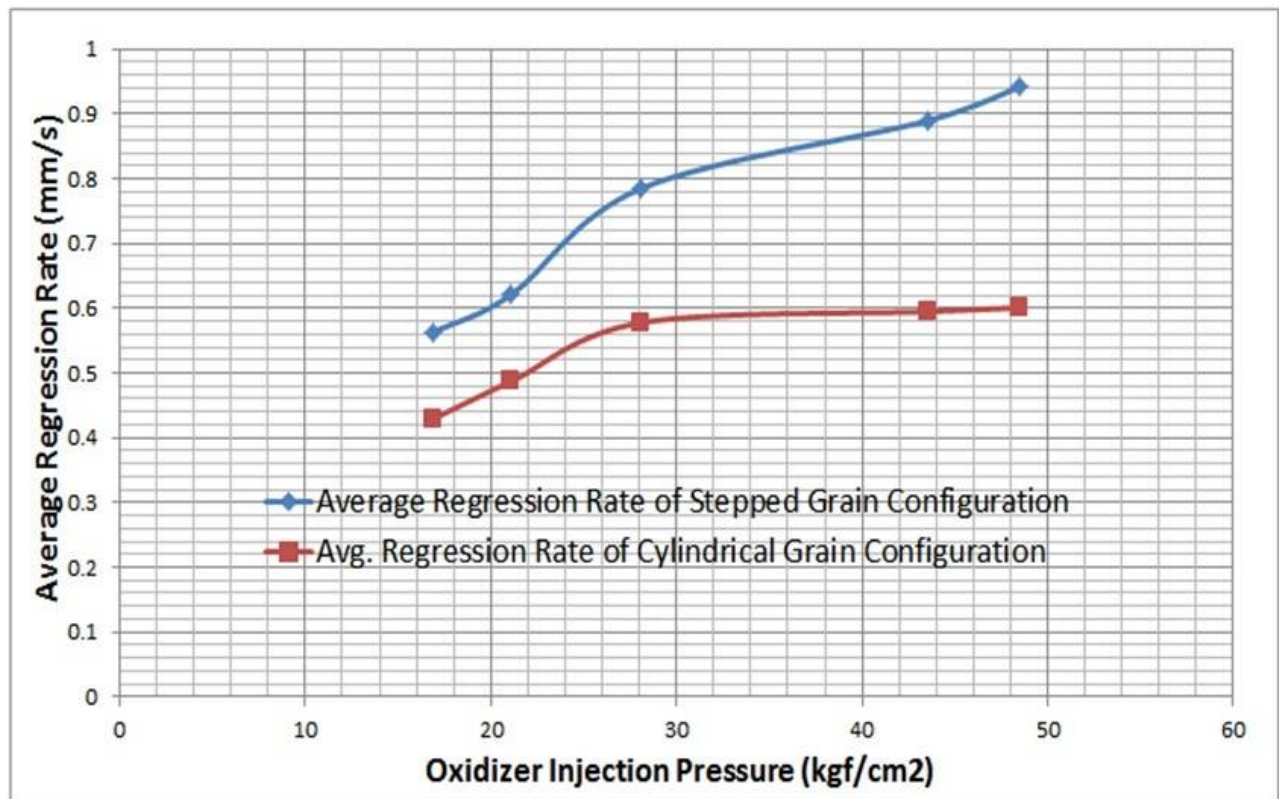


Fig – 5

### Fuel Mass Burn Rate;

The fuel mass consumption rate in both the grain configuration at various injection pressures have been compared and presented in Fig-6 As expected with increasing oxidizer injection pressure the fuel mass flow rate

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increases because of increase in regression rate of fuel surface. Similar results came out in present investigation. We observed lesser fuel mass consumption rate in the case uniform cylindrical grain configuration compare to cylindrical stair grain configuration at particular oxidizer injection pressure.

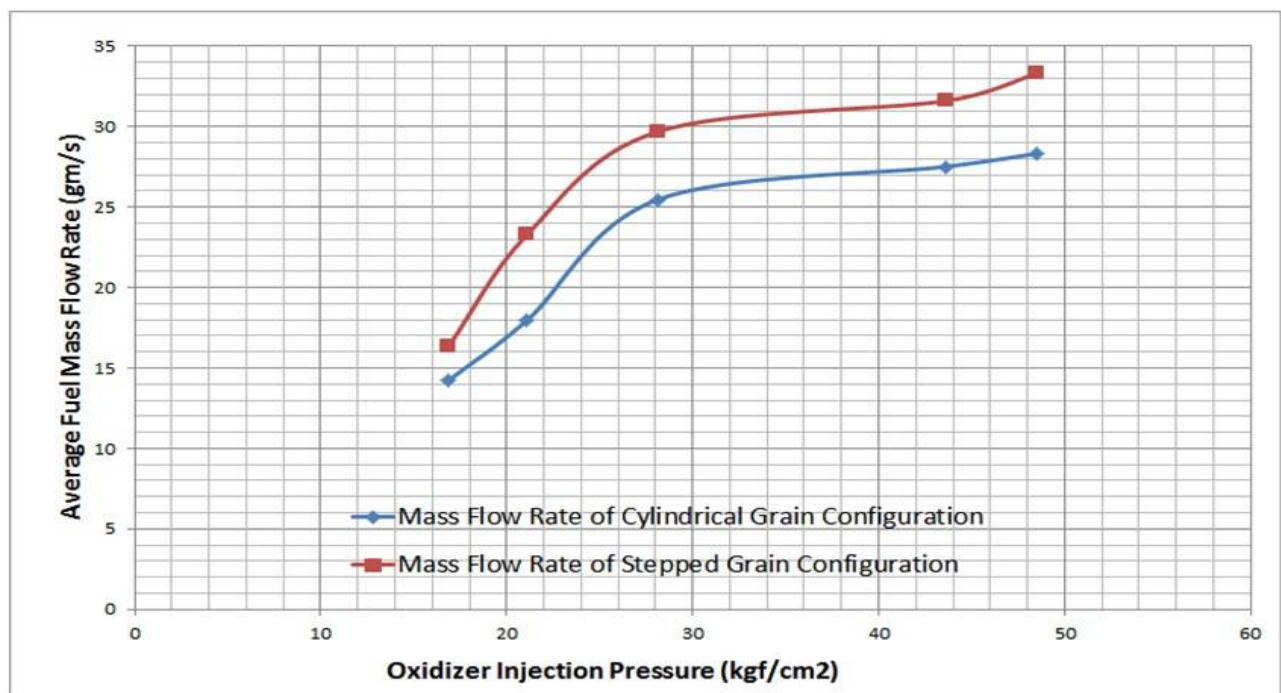


Fig – 6

## V. CONCLUSION

In the present work, an attempt has been made to overcome the problem of low regression of solid fuel grain in hybrid rocket motors by changing the grain port configuration one cylindrical other stair grain configuration. The regression rates have been measured at different injection pressure in two grain configuration. The regression rate of these grain configurations has been compared and discussed. Some significant conclusions could be drawn from the investigation. Some notable conclusion has been presented below.

1. In case of uniform cylindrical port grain local regression rate drop sharply and after that remains more or less constant in most of the part of the grain except at the end.
2. In case of stepped port fuel grain the local regression rate has been found nearly similar to cylindrical grain at the head end but the uneven regression took place along the length of the grain.
3. The average regression is found to be more in case cylindrically stepped fuel grain configuration as compared to normal cylindrical grain at particular oxidizer injection pressure.
4. The exhaust plume has been found to be bright in all the cases, showing proper mixing of fuel and oxidizer for complete combustion. Smoke has been found almost negligible.
5. The maximum flame diameter of cylindrical stepped grain configuration has been observed compare to normal cylindrical grain configuration.
6. In all the cases, the soot has been deposited on the nozzle and on the swirl injector plate. It may be because the pyrolysis of fuel surface even after termination of oxidizer flow.



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7. The fuel mass flow rate has been found more in cylindrical stepped grain when compared to other grain configuration.

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