

Regression Rate Study of Cylindrical Stepped Cosine Shaped Fuel Grain in Hybrid Rocket

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ABSTRACT: Hybrid rocket propulsion is a rising propulsion system having features such as low cost, safety and environment friendliness. Despite of such features it has certain issues like mixture ratio shifting; low regression rates, mixing inefficiencies etc. which bound its use as a prime propulsion system. Amongst all these issues the present analysis represents an approach for rectification of one of the most important issue namely, low fuel regression rate. The 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. (By inducing an oxidizer vortex into the combustion chamber improving shear stress and thus regression rate.) The Cylindrical Stepped Cosine Shaped Fuel Grain 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. To investigate the solid-fuel regression rate behaviour and operating characteristic of stepped solid fuel grain hybrid rocket motor a series of static rocket firing were conducted. 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/cm²) respectively. Compared to cylindrical grain, a higher regression rate has been observed in the case of cylindrical stair fuel grain.

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

I. INTRODUCTION

Over the traditional solid and liquid rocket propulsion system shown in fig.1, hybrid rocket propulsion system carries distinct advantages such as thrust flexibility, low environmental pollution, grain robustness, and propellant versatility. Hybrid propulsion system is superior in many aspects as compared to solid propulsion system or liquid propulsion system. Considering its merits, efforts had been made to develop a hybrid propulsion system across the globe.

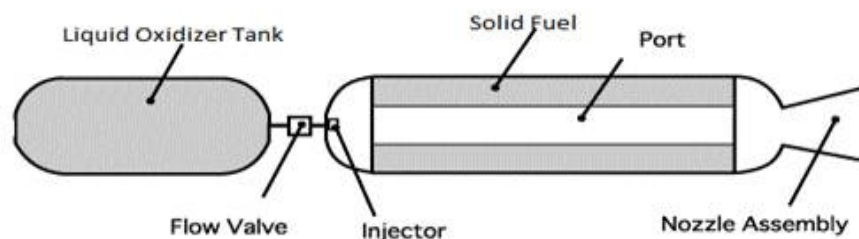


Fig. 1: Schematic Diagram of Hybrid Rocket Propulsion System

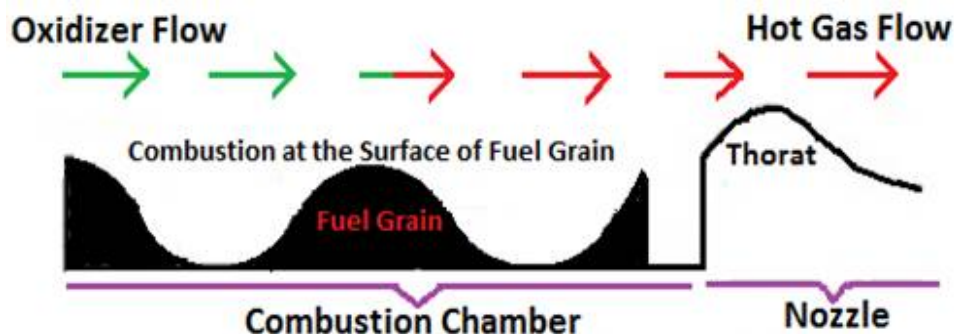
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A number of hybrid propellant combinations have been investigated to find a viable system and on the other hand a number of combustion models have been developed and a number of regression theories came out for efficient design and development of hybrid system. Owing to large number of advantages over conventional hybrid fuel grain much attention has been paid to design a stepped fuel grain in order to increase the mass regression rate. During the combustion inside the grain a stepped grain is supposed to create circulation in the flow. Circulation in the flow form vortices 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. Earlier researchers have deeply investigated the combustion process in hybrid rocket. However to provide the basis for design of hybrid rocket fuel grain, full scale engine and to achieve optimum combustion performance sufficient knowledge has been acquired. In the study of hybrid rocket combustion the solid-fuel regression rate is a very important design and ballistic parameter.



2-D view of half cut of hybrid rocket motor.

Fig.2: Hybrid Rocket Motor with Cylindrical Stepped Cosine Shape Fuel Grain

II. RELATED WORK

Bartel and Rannie gave the first analytical treatment of hybrid combustion [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, $G_{ox}=90\text{kg/m}^2\text{sec}$. Houser and Peck investigated the combustion behavior of polymer based fuel (Plexiglas), in which the burning surface was a cylindrical hole, 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

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radiant heat transfer term in regression rate equation to account for thermal radiation improved empirical correlations for metal-loaded fuels.

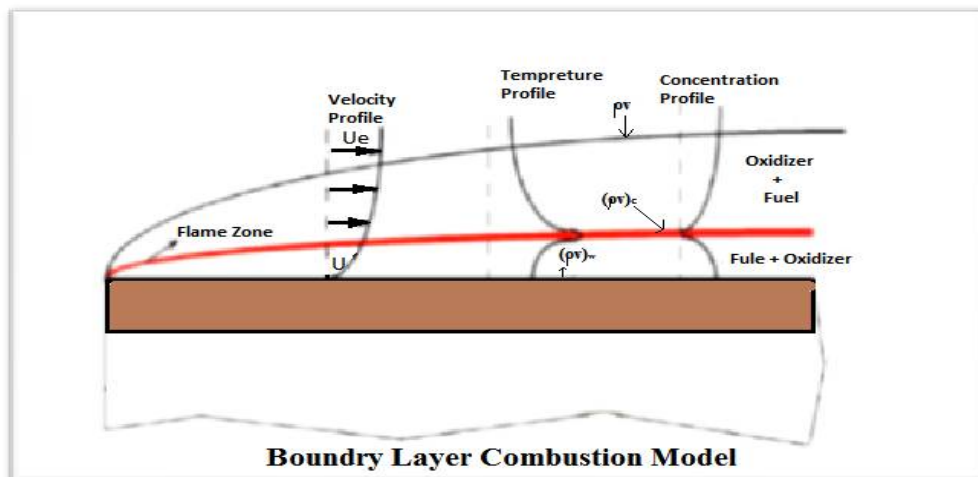


Fig. 3: Basic Model of Solid fuel Combustion

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 rates with oxidizer flow. Regression rate was found to be nearly independent of partial pressure at the lowest flow rate domain whereas, pressure dependence was found to be greatest at high flow rates. Their correlation predicted that the experimental regression rates to within $\pm 40\%$. Karabeyoglu et al developed the regression-rate model based on Liquid layer entrainment mechanism [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 low regression rate of solid fuel is the basic problem that degrades the application of hybrid motors. To overcome this problem in hybrid rocket many studies was 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.

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By increasing oxidizer flow speed over the burning fuel surfaces, the fuel regression rate can be increased. This happens because the flow over the burning surface creates shear stress which facilitates fuel and oxidizer mixing. By inducing an oxidizer vortex into the combustion chamber, shear stress and the regression rate can be improved.

One of the mean is the stepped fuel grain configuration, to create the vortex combustion field in a port. Injecting oxidizer axially in the fuel grain and vortex created inside the grain due to different size of cylindrical port size, this flow can be generated. To test the solid fuel regression rate behaviour and operating characteristic of the cylindrical stepped cosine shaped fuel grain hybrid rocket motor, a series of static rocket firing were conducted. Using polyvinyl chloride and gaseous oxygen, the results from eight different tests of laboratory scale hybrid rocket motor have been presented here at different oxidizer injections pressures i.e. 16.872, 21.092, 28.122, 42.184, and 48.511 (kgf/cm²) respectively. To carry out the research programme as planned, the experimental works were done in the following area.

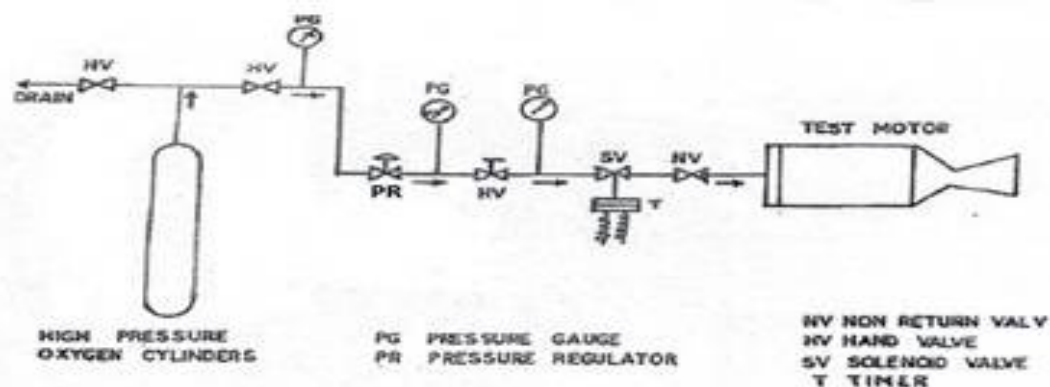


Fig.4: Line Diagram Hybrid Rocket Test Firing

- **Test Equipment**

The test hybrid motor consists of the following, the oxidizer assembly, injector plate, and combustion chamber with solid fuel grain loaded and nozzle. The 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. The eight holes have been apart at 128 mm p.c.d. for swirl injector, drilled at angle of with the axis to ensure Swirl type of injection. In the test, gaseous oxygen feed system is used and feed system is composed of pressure regulator, check valve, and flexible Teflon hoses. The cylindrical shape combustion chamber is provided with an outer-jacket for coolant passage. It's 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. To hold nozzle with the combustion chamber having six equidistant holes of 14mm diameter at 128 mm, a nozzle retainer ring made of mild steel was used. Oxygen is injected into port of fuel grain and the fuel grain is directly cast into chamber. Fig.4 represents Section View of Hybrid Rocket Motor.

- **Fuel Grain Specimen**

The composition of Polyvinyl Chloride (PVC) and Dibutylphthalate (DBP) were evaluated in each case and compared alone fuel grain, for the present test. For preparation of fuel grains commercial grade polyvinyl chloride and laboratory grade Di-butyl phthalate were used. 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, PVC plastisol was chosen as fuel. Di-butyl phthalate (DBP) was taken in a stainless steel beaker and heated it first fumes to remove the moisture. It was then cooled down to room temperature. For about an hour, PVC was dried at 550-600 to remove moisture. In a horizontal sigma blade mixer the required quantity of PVC

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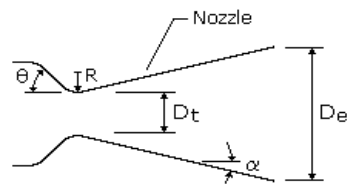
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and DBP were mixed thoroughly. To ensure uniformity in the fuel mixture, the mixing was carried out for a period of 3 hr.



Fig. 5: Swirl Injector



Nozzle Dimension Detail:-

1. Throat Diameter = 12mm
2. Nozzle Exit Diameter = 33.3mm
3. Nozzle Inlet Diameter = 79.5 mm
4. theta = 45 degree
5. Alpha = 25 degree



Fig. 6: Convergent Divergent Nozzle with Cooling Mechanism



Fig.7:Hybrid Rocket Static Test Firing Set-up

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To ensure uniform mechanical properties the mixing conditions were maintained uniform in all the mixing. The fuel mixture was cast in aluminium mould having inside diameter 76mm and length 270mm and fitted with a mandrel. Two different diameter mandrel i.e 25mm and 35 mm were used in present work to get the fuel grains of 25mm and 35mm port diameter. With help of a push fit block the top of the mould was closed. The provisions were made in the top and bottom enclosure to retain the mandrel at the centre and the axial locations of the mould. Prior to filling process, the mould and mandrel were cleaned and coated with petroleum jelly to facilitate easy extraction of grain. The filled mould was cured at 1200C for 3 hours and after that kept at room temperature to cool down. The fuel grain was extracted from the mould manually, trimmed, checked for cracks and bubbles then to avoid contamination it was stored in polythene bags. To make cylindrical stepped cosine shaped fuel grain, grains were joined alternatively by using araldite, of two different inner diameters I.D = 51 & 56mm and outer diameter 76mm of length 60 mm. The length of the grain was 240mm. 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. For an hour the motor was kept in oven 1200C for curing the inhibitor and then it was allowed to cool down to ambient temperature.



Fig. 8: Sigma Blade Mixture

• 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 Nichrome wire. For electrical connections the end of coil was soldered with long enamelled copper wire. The secondary igniter was made with the beads of the above composition. The beads were sealed in a polythene bag. The bag was tightly closed with the help of adhesive tape after the primary igniter was inserted in it.

• Test procedure

In the combustion chamber the Igniter was placed at the head of the grain. With the help of nuts and bolts the swirl injector was fitted at head end of the chamber. Nozzle was fixed with the help of nozzle retaining ring. On the test bed the test motor was mounted rigidly and at the inlet of the oxidizer chamber oxygen gas line was connected to the adaptor. 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/cm² to 48.511kgf/cm²) 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

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injected as soon as the igniter fired and the combustion was terminated after a lapse of pre-requisite duration by cutting off the oxidizer flow. For about duration of 10 sec the combustion of fuel grains were carried out. From the combustion chamber the fuel grain were taken out after each test firing and with the help of a sharp knife, were cut along the length at four points for visual inspection and measurement of the un-burnt web thickness along the length of the fuel grain. To determine the mass consumption rate the fuel grain was weighed after firing. The local regression rate was determined by measuring the un-burnt web thickness at each centimetre 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. By the difference of weights before and after firings the mass consumption rate was determined 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.

IV. EXPERIMENTAL RESULTS

In the present investigation, an attempt has been made to study the combustion characteristics of a PVC hybrid fuels. The local regression rate of uniform port cylindrical fuel grain is present in Fig-9 for different oxidizer injection pressure i.e 16.872, 28.122, 42.184 (kgf/cm²) respectively. It is noticeable 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 local regression rate of hybrid fuel grain is found to increase with increase in Oxidizer injection pressure and the similar patterns of variation of local regression rate were found at all oxidizer injection pressure.

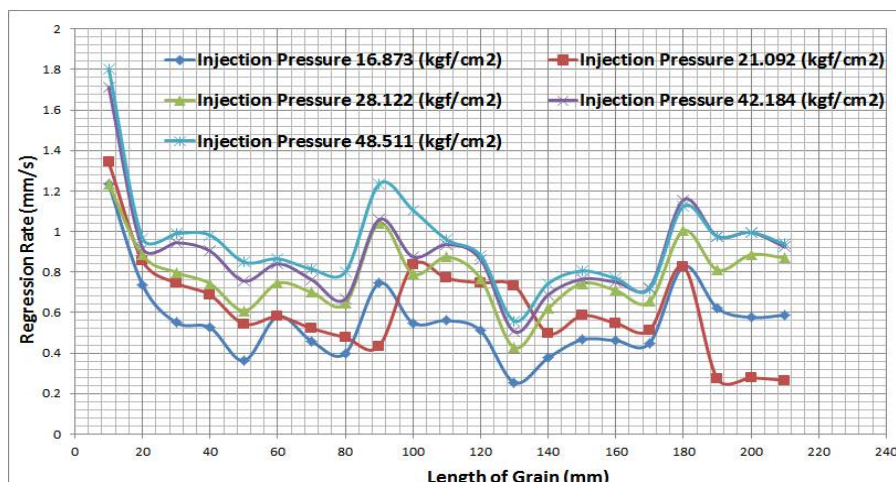


Fig. 9: Comparison of Normal Cylindrical Grain with Cylindrical Stepped Cosine Shaped Fuel Grain

With the use of swirl injector, results in the regression rate at the leading edge is more as direct impingement of oxygen at the inlet of fuel port results in high oxidizer concentration and heterogeneous chemical reaction. Also, the regression rate is obvious to be high at the head end as the flame zone is close to the grain port. Along the length of the solid fuel grain the oxidizer is depleted and reduced. On the other hand, as we move forward the mass flux keeps increasing. 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, flame zone moves away from the fuel surface as the boundary layer grows along the grain length. Hence regression rate shows a decreasing trend as the heat transfer from flame zone to fuel surface is decreased along the length. Before the nozzle end,

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regression is increasing; the excessive heating of the grain because of accumulated high temperature combustion gases in the free space after the grain and may be due to this value of regression rate increases.

The local regression rates of cylindrical stepped cosine shaped fuel grain for different oxidizer injection pressure i.e. 16.872, 21.092, 28.122, 42.184, and 48.511 (kgf/cm²) respectively. As regression rate being highest at the head end but after that the uneven regression of grain surface was found till nozzle end, in this case the trend has been found similar to normal cylindrical grain. Compared to lesser port I.D grain segment the higher port I.D of grain segment has lower regression rate. The local regression rate of hybrid fuel grain is found to increase with increase in oxidizer injection pressure and the similar patterns of variation of local regression rate were found at all oxidizer injection pressure.

Grain Configuration	Injection Pressure (kgf/cm ²)	Chamber Pressure (kgf/cm ²)	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	0.3628	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	-	0.421	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	0.5854	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	0.69	29.24	103.56	135.17
Cylindrically Stared Shape Grain	46.511	10.827	0.74252	33.65	115.798	149.11

Table 1:Data Sheet

Higher but not even regression on the surface of stair fuel grain may be because of the 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. This enhances the heat transfer to the regressing surface causes more uniform mixing of gas phase reactants. As a result, it enhances the fuel burning rate. Second the vortex formation increases the mixing of the gas phase reaction. Third enhancing the fuel regression rate is due to vortex flow as it increases the shear force on the surface of grain. Fourth as the oxidizer flow vortex tries to move towards the nozzle side results 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. Similar results came out for both the grain configuration in the present investigation. We observe that comparative to the normal cylindrical grain at particular the injection pressure, the average regression rate is more in the case of stair

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grain configuration. The result shows that to get higher regression rate, the stepped grain configuration can be an alternative option in hybrid propulsion system.

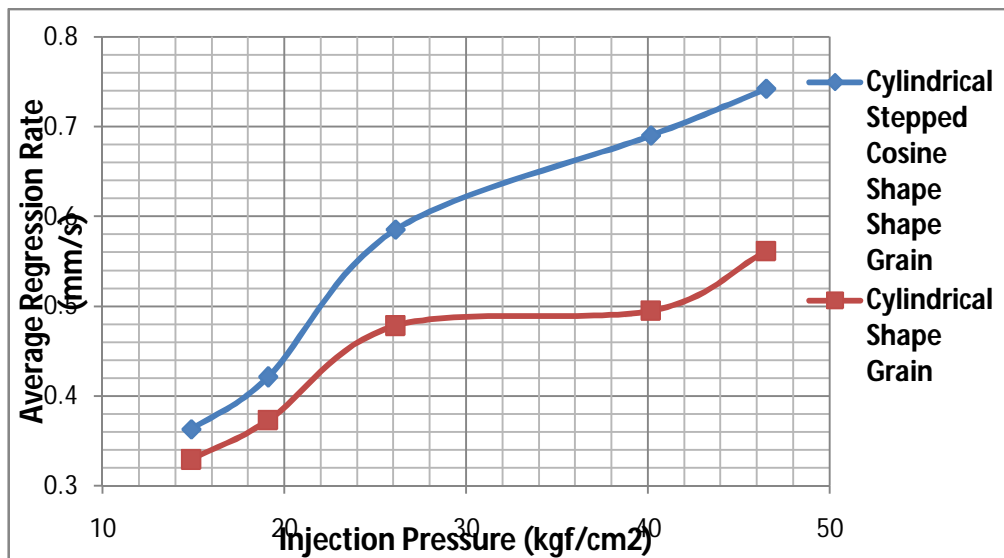


Fig. 10: Average Regression Rate with Oxidizer Injection Pressure

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

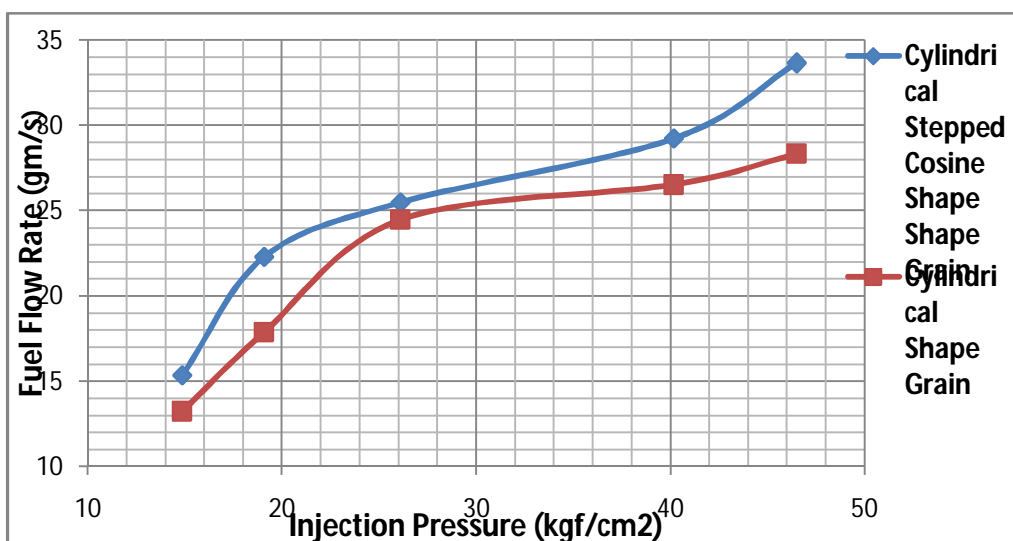


Fig. 11: Fuel Mass Flow Rate with Oxidizer Injection Pressure

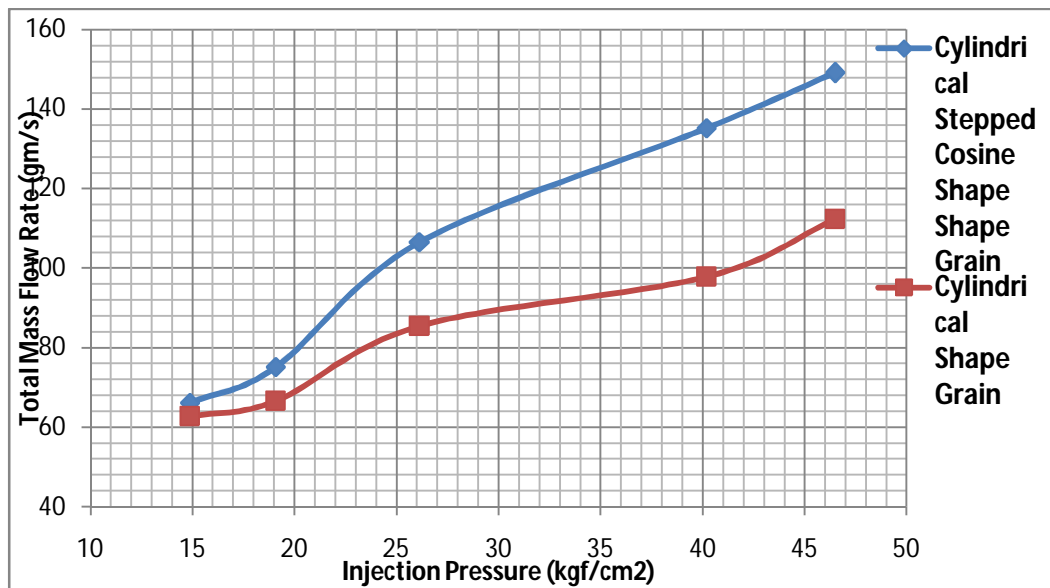


Fig. 12: Total Mass Flow Rate with Oxidizer Injection Pressure

V. CONCLUSION

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

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

REFERENCES

- [1] Alexandra Lazarev, Alon Gany, 'Experimental Investigation of Paraffin-Fueled Hybrid Combustion', Technion – Israel Institute of Technology, Haifa 32000, Israel', Third European Combustion Meeting ECM 2007.
- [2] C. Carmicino, F. Scaramuzzino and A. Russo Sorge, 'Trade-off between paraffin-based and aluminium-loaded HTPB fuels to improve performance of hybrid rocket fed with N₂O', Aerospace Science and Technology 37 (2014) 81–92.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 5, May 2017

- [3] Sandeep Patnala, Tribikram Chattaraj and P. C. Joshi, 'Combustion Studies on Paraffin Wax in Gaseous Oxygen and Nitrous Oxide', ARPN Journal of Engineering and Applied Sciences, Vol. 7, No. 7, July 2012, ISSN 1819-6608.
- [4] R.N.Kumar and D.B. Stickler, 'Polymer thermal degradation theory of pressure sensitive hybrid combustion, calculating linear regression rates', SYMPOSIUM /INTERNATIONAL/ ON COMBUSTION; 13TH; AUG. 23-29, 1970; 71A38123.
- [5] Yash Pal, Kalpit.K and P.K.Dash, 'Regression Rate Study of PVC/HTPB Hybrid Rocket Fuels' International Journal of Mechanical & Industrial Engineering, Volume-1 Issue-1, 2011.
- [6] S. Venugopal, V. Ramanujachari and K.K. Rajesh, 'Design and Testing of Lab-scale Red Fuming Nitric Acid/Hydroxyl-terminated Polybutadiene Hybrid Rocket Motor for Studying Regression Rate', Defence Science Journal, 2011, 61(3), pp.193-200.
- [7] Dr A K Chatterjee and S Som, 'Influence of Oxidiser Incorporation in PVC Plastisol Hybrid Fuel' IE (I) Journal AS, Vol 84, November 2003.
- [8] Chatterjee A.K. and Joshi P.C., 'pressure dependence of PVC plastisol burning in gaseous oxygen', J. of spacecrafts and rockets, Vol.14, No. 6, June 1977, pp. 738-739.
- [9] Rajiv Kumar and P.A.Ramakrishna, 'Measurement of regression rate in hybrid rocket using combustion chamber pressure', Acta-Astronautica 10/2014; 103:226-234.
- [10] Martin J. Chiaverini, Nadir Serin, David K. Johnson, Yeu-Cherng Lu, Kenneth K. Kuo, and Grant A. Risha, 'Regression Rate Behavior of Hybrid Rocket Solid Fuels', Journal of Propulsion and Power, Vol. 16, No. 1 (2000), pp. 125-132.
- [11] C. Palani Kumar and Amit Kumar, 'Effect of swirl on the regression rate in hybrid rocket motors, Aerospace Science and Technology 29 (2013) 92-99.
- [12] Akiba R. kohno M., Higashi T. and Furnyama Y., 'some investigation on powder hybrid propulsion', proc. X international symposium on space technology and science, Tokyo, 3-8 sept. 1973, pp.125-134.
- [13] Marxman G.A. and Gilbert M., 'turbulent boundary layer combustion in hybrid rocket', IXth symposium (international) on combustion, combustion institute, Pittsburgh, 1962, PP. 371-383.
- [14] B. Wasistho and R. D. Moser, 'Simulation Strategy of Turbulent Internal Flow in Solid Rocket Motor', Journal of Propulsion and Power Vol. 21, No. 2, March-April 2005.
- [15] Akiba R. kohno M., Higashi T. and Furnyama Y., 'some investigation on powder hybrid propulsion', proc. X international symposium on space technology and science, Tokyo, 3-8 sept. 1973, pp.125-134.
- [16] Penner S.S., 'Chemical Rocket Propulsion and combustion research', Gordan and Breach, New York, 1962, PP.145-153.
- [17] Manish Kumar and Dr. P C Joshi, "Regression Rate Study of Cylindrical Stepped Fuel Grain of Hybrid Rocket" published International Conference on Advancements in Aeromechanical Materials for Manufacturing (ICAAMM-2016) organized by Elsevier www.materialstoday.com/proceedings.

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