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Regression Rate Study of PVC/HTPB Hybrid Rocket Fuels

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Abstract—In the present study an effort is made to investigate the local regression rate, average regression rate through the effect of oxidizer injection pressure. For experimental investigation a lab scale ballistic test motor is designed and number of static test firing are carried out at different gaseous oxidizer injection pressure. The injection pressure is varied from 150psi to 420psi and a Swirl Injector and a conventional Shower Head Injector are used for the oxidizer injection from oxidizer chamber to fuel grain port. The local regression rate is obtained from the unburnt fuel web thickness after 10.5 second of test firing. Further, the investigation of regression rate of PVC and HTPB solid fuels are depended on mass flux of oxidizer as the regression rate shown a decreasing trend from head end to nozzle end. From the present analysis, it can be summarized that for PVC solid fuel regression rate is completely dependent on swirl injection of oxidizer, as well as the oxidizer injection pressure.

Keywords-Regression rate,mass flux,HTPB,PVC ;

NOMENCLATURE

$\dot{r}$	Regression Rate
G	Total mass flux
x	Distance Along Fuel Grain
G_{ox}	Gaseous oxidizer
HTPB	Hydroxyl-Terminated polybutadiene
PVC	Polyvinyl Chloride

I. INTRODUCTION

Hybrid rocket propulsion system possess distinct advantages such as thrust flexibility, low environmental pollution, grain robustness, propellant versatility over traditional solid and liquid rocket propulsion system. The combustion process in hybrid rocket was deeply investigated by earlier researcher. 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 the important design and ballistic performance parameter in the study of hybrid rocket combustion. The first analytical treatment of hybrid combustion was provided 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, Gox=90kg/m2sec. 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 ($\dot{r} \propto G^{.08}$). Furthermore, the regression rate was a weak function of the axial distance ($\dot{r} \propto x^{-02}$). 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 rates with oxidizer flow. Pressure dependence was found to be the greatest at high flow rates, where as regression rates 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 ±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 increased 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 Gox.

II. EXPERIMENTAL SETUP

In the present experimental work, the regression rate study of Hydroxyl Terminated Polybutadiene (HTPB) and PVC Plastisol hybrid fuel are carried out in a stream of gaseous oxygen oxidizer using the head end injection test motor. To carried out experimental investigation, fuel loaded (HTPB) in test motor fired using a conventional Shower Head Injector, while the static test firing of the PVC fuel loaded motor is carried out with swirl Injector. Fig.-1 represents the details of the experimental setup used in the present investigation.

A. 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 147mm diameter, 14.5mm thick, with 9mm diameter holes and a cup shaped oxidizer chamber of length 66mmand diameter of 63mm.For swirl injector eight holes have been 45^0 apart at 29 mm p.c.d., drilled at angle of 2.5^0 with the axis to ensure Shower Head 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 with throat diameter 10mm and nozzle area ratio 9.6 has been chosen. The fuel grain is directly cast into chamber and oxygen is injected into port of fuel grain. Fig.2 represents Section View of Hybrid Rocket Motor

B. Fuel Grain Specimen

For present test, the composition of Polyvinyl Chloride (PVC) and Dibutylphthalte (DBP) were evaluated in each case and compared alone fuel grain. selected as solid fuel. After several composition tests, the 50 % (by wt) PVC and 50% (by wt) DBP gives best performace.The mixture of PVC&DPB was heated to 56^0C for several hours to remove the moisture and then thoroughly mixed in six sigma blade mixture for 2 and half hour to ensure the uniformity of fuel mixture and mechanical properties. This mixture is then cast into aluminum mould, before filing process; the mould was cleaned with petroleum jelly to facilitate easy extraction of fuel grain. The mould was kept on vacuum casting unit to provide vibration for optimum mixing and to avoid the void formation. Then mold was cured at 120^0C for 2 hours. For HTPB grain, requisite quantity of HTPB and glycerol were mixed thoroughly in a steel beaker. The mixture was stirred continuously for one hour for homogeneity and after that TDI was added in it with continues stirring for half an hour. The mixture was kept as it is for 24 hours. After 24 hours, it was vacuum caste in the appropriate mould to get the required shape and size of the grain. Some of the physical properties of HTPB and PVC Fuel are given in Table - 1.

C. Test procedure

The fuel grains of required size were loaded in test motor with an inhibitor made from chalk powder. Then the motor was cured at 120^0C for 2hour.The pyrogen igniter, placed at head end of grain, was ignited and maintained for 3sec. Oxygen stored in high pressure cylinder was regulated with help of regulator valve-inline and injected as soon as the igniter ignited. The combustion was terminated after desired firing duration with the help of oxygen supply cut-off. Test was carried out for four different–injection pressure as shown in Table-1.The test measurement were local fuel regression rate and mass consumption rate and other pre-measurement fuel density, temperature ,initial and final nozzle diameter, grain dimension. Bomb calorimeter was used to measure the heat of combustion of fuel grains. A small quantity about 1gm was burnt in the bomb at 300 oxygen pressure.

III. RESULTS AND DISCUSSIONS

In the present investigation, an attempt has been made to study the combustion characteristics of HTPB and PVC hybrid fuels. These fuel grains are subjected to regression study in a stream of oxygen at different injection pressures using head end injection test motor. Hybrid fuel combustion parameter such as local regression rate, average regression rate and mass consumption rate are

A. Local Regression Rate;

The variation of local regression rate along the length of fuel grain at oxygen injection pressure 150psi, 240psi, 300psi, and 420psi for HTPB fuel grain has been presented in Fig-3. The pretest and posttest measured data for HTPB solid fuel is presented in Table-3. It has been observed that the regression rate is highest at the leading edge in all oxygen injection pressures. After that the regression rates shows a decreasing trend up to a certain length along the grain length and then maintain a more or less constant value except at the end of the grain, where it is shown a somewhat increasing trend. Similar trends of variation of local regression rate along the length of the grain are observed in case of PVC fuel grain. However, at head end of solid fuel grain the local regression rate do not decrease as sharply as has been seen in HTPB fuel grain firing data. The results are presented in Fig- 4. The pretest and posttest measured data for PVC solid fuel is presented in Table-4.

The local regression rate at the leading edge has been shown peaks which are due to high oxidizer concentration and heterogeneous chemical reaction by direct impingement of oxygen at inlet port of fuel. As the distance along the solid fuel is increased the concentration of Gox is decreased and heterogeneous reaction intensity decreased. Regression rate is contributed and controlled by the heat feedback from the flame to solid fuel surface. However, as the boundary layer grows along fuel grain the flame zone moves away from the fuel surface .Hence the heat feedback from flame zone to fuel surface is decreased along the length and regression rate shows a decreasing trend.

B. Average Regression Rate ;

The variation of average regression rate of the fuels with oxidizer injections pressure has been presented in Fig 4. The average regression rate of HTPB shows a lower increase in average regression rate with increase of oxidizer injection pressure as compared to the PVC fuel. Increase of oxidizer injection pressure, will enhance the oxidizer mass flux which will result in higher flame temperature and so higher available heat flux at the fuel surface for regressing the fuel. The higher value of average regression rate for PVC fuel grain as compared to the HTPB fuel grain may be attributed due to the heat available at the burning surface from the flame and enthalpy of vaporization of solid fuel. To check the energetics of fuel an estimation of heat of combustion of HTPB and PVC fuel were carried out in an isothermal bomb calorimeter and results are presented in Table-2. It was found that the heat of combustion of PVC is much higher (8913.86cal/gm) as compared to HTPB fuel (7931.6cal/gm). The fuel having higher heat of combustion is expected to produce higher flame temperature as compared to the fuel having lower heat of combustion and thus higher heat flux at the fuel surface.

C. Fuel Mass Burn Rate;

The variations of fuel mass consumption rate with oxidizer injection pressure are presented in Fig-6. The fuel consumption rate is found to increase exponentially with the oxidizer injection pressure for both fuel grains. However, the fuel consumption rate is highest for PVC fuel this attribution is due to swirl injection of oxidizer into test segment as compared to axial injection of oxidizer in case of HTPB fuel grain firing. The swirl injector leads to higher the oxidizer flow rate and more fuel is expected to consume. The schematic views of HTPB and PVC solid fuels firing on test stand are presented in Fig-7 to Fig.-8.

IV. CONCLUSIONS

In the present study an effort has been made to investigate the local regression rate, average regression rate, effect of oxidizer injection pressure. Based on the work carried out in the present investigation, the following conclusions are drown

1. It has been observed that the regression rate is highest at the leading edge in all oxygen injection pressures.
2. For PVC fuel grain, the local regression rate at head end of solid fuel grain did not decrease as sharply as has been seen in HTPB fuel grain firing data.
3. The average regression rate was found to be more for PVC fuel grain at each injection pressure as compared to HTPB fuel grain.
4. The fuel consumption rate was found to increase exponentially with the oxidizer injection pressure for both fuel grains.
5. The use of swirl injector was attributed to increase the fuel mass consumption rate and hence fuel regression rate.

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FIGURES AND TABLES

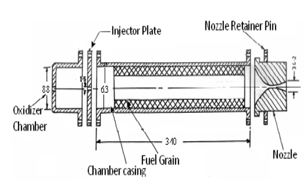

Figure.1 Section View of Hybrid Rocket Motor

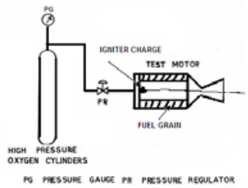

Figure.2 Schematic of experimental setup

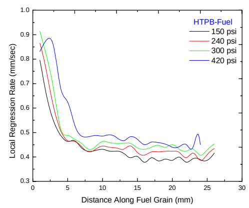

Figure.3 Variation of Local Regression rate of HTPB-Gox with Injection Pressure

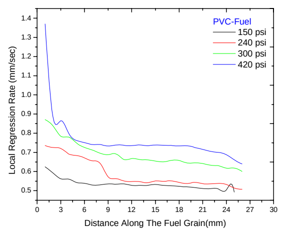

Figure.4 Variation of Local Regression rate of PVC-Gox with Injection Pressure

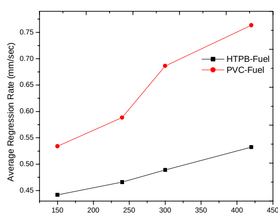

Figure.5 Effect of Oxidizer Injection Pressure on Average Regression Rates

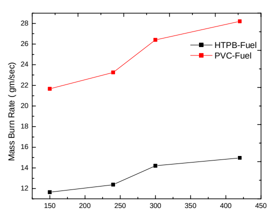

Figure.6 Effect of Oxidizer Injection Pressure on Mass Burn Rate

Figure.7 Schematic View of Solid Fuel (HTPB) Firing on Test Stand

Figure.8 Schematic View of Solid Fuel (PVC) Firing on Test Stand

Table 1 Physical Property of PVC and HTPB Hybrid Fuels

Hybrid Fuel	**HTPB**	**PVC**
Property	**Value**	
Molecular mass (gm/k mol)	138000	100000
Heat of gasification (kJ/kg)	1800	1300-2700
Thermal conductivity (W/m.k)	0.217	0.17-0.19
Density(g/cm^3)	0.92	1.18
Heat of formation (kJ/mol)	-51.8	-430.5
Activation energy	16.9	34.15

Table 2 Measured Calorific Values of HTPB and PVC Solid Fuel

S.No.	**Calorific values of Hybrid Rocket Fuels(cal/gm)**	
	HTPB	**PVC**
1	7986.3	8933.1
2	7912.2	8912.2
3	7896.3	8896.3
Average Calorific values	7931.6	8913.867

Table 3 Pretest and Posttest Results for PVC Solid Fuel

Injection Pressure psi	**Initial Fuel Web Thickness (mm)**	**Mass Burn Rate gm/sec**	**Firing Duration sec.**	**Avg. Regression Rate mm/sec**
150	15	21.66	10	0.533952
240	15	23.25	10	0.588346
300	15	26.4	5.88	0.686423
420	15	28.2	6.70	0.763462

Table 4 Pretest and Posttest Results for HTPB Solid Fuel

Injection Pressure psi	**Initial Fuel Web Thickness (mm)**	**Mass Burn Rate gm/sec**	**Firing Duration sec.**	**Avg. Regression Rate mm/sec**
150	15	11.64	10.5	0.441741
240	15	12.38	10.5	0.466075
300	15	14.2	10.5	0.488967
420	15	14.97	10.5	0.532395