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Effect of protrusion on the enhancement of regression rate

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ABSTRACT

It has been reported in literature that the use of protrusion in the combustion chamber of a hybrid rocket motor enhances the regression rate. A detailed study was carried out by using two types of protrusion (a) rubber (which burns along with fuel but at different rate, hence its shape changes with burn time), and (b) graphite (does not burns along with fuel and hence its shape does not changes with burn time). The results showed that the improvement in regression rate with protrusions was only up to a certain fraction of the overall burn time. From the results obtained, it was observed that an X/L of 0.5 was the best location for both types of protrusion. The maximum improvement in regression rate was around 45%. The combustion efficiency was observed to improve from 58% without protrusion to 69% with the use of protrusion, when placed at an X/L of 0.8. It was observed that the use of bluff body and protrusion improves combustion efficiency, when used individually. Hence, combination of the two was used and the combustion efficiency was determined. The combustion efficiency was around 90%, when bluff body was used at the head end and the protrusion at an X/L of 0.8 from head end.

1. Introduction

Hybrid rocket contains fuel and oxidizer in different phases, generally fuel is in solid phase and oxidizer is in gaseous or liquid phase. Hybrid rocket is known to be safer compared to the solid and liquid rocket engines. The advantages of hybrids are well documented by Sutton and Biblarz [19]. A detailed of this can also be found in AIAA book [3] and in the review paper by Pastrone [17].

The major drawbacks of hybrid rocket are low fuel regression rate and low combustion efficiency. In order to overcome both these drawbacks without compromising on volumetric loading, Boardman et al. [2] have advocated the use of protrusions in the port of the hybrid rocket. The study of protrusion in hybrid rocket has important implications, as protrusions alter the flow behavior within the combustion chamber and hence is independent of the type of fuel or oxidizer.

It has been reported by Boardman et al. [2] that using a wire screen periodically in the fuel grain normal to the axis, increases the heat transfer to the fuel surface, which in-turn increases the regression rate. An attempt was also made by Osmon [16] to improve the combustion efficiency by placing a tabulator of thickness 2 inch at the downstream of the fuel grain. He observed a marginal improvement in the combustion efficiency from around 84–86%. Gany and Timnat [4] had proposed the use of a diaphragm which had a thickness of around 10 mm and was made of phenolic asbestos. The fuel used in the study was the combination of polyester along with Al and AP, oxidizer used was RFNA. They observed an improvement in the regression rate of about 50%. The combustion efficiency obtained was around 97–98% with the combinations of appropriate injectors and diaphragms. They did not observe any improvement in the combustion efficiency on varying the locations of diaphragm in the combustion chamber. Grosse [6] has used micro-crystalline wax as fuel and nitrous oxide as oxidizer. He advocated the use of a diaphragm in the combustion chamber in order to enhance the regression rate and provide better mixing in the combustion chamber such that the combustion efficiency will improve. He observed an improvement in the combustion efficiency, which reduces with the increase in O/F ratio for all axial location of diaphragm. The regression rate was also seen to improve at locations downstream of the diaphragm by about 40% with a one hole diaphragm placed at an axial location of 33% from the head end, while the improvement was around 80% with a 4 hole diaphragm.

The burn time used by Gany and Timnat [4] varies between 4 and 25 s and that used by Grosse [6] varies between 3 and 7 s. The regression rate was obtained by weight loss method and was averaged for the above burn time. However, during combustion, the port diameter increases, and therefore protrusion height increases continuously in both their cases. The size of recirculation

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Nomenclature

Al	Aluminum	$\dot{m}_{ox}$	Mass flow rate of oxidizer .... g/s
AP	Ammonium perchlorate	n	Flux exponent
A_t	Throat area .... m^2	O/F	Oxidizer to fuel ratio
C^*	Characteristic velocity .... m/s	$\dot{r}$	Regression rate .... mm/s
C^*_{exp}	Experimental characteristic velocity .... m/s	r_i	Intial port radius .... m
C^*_{theo}	Theoritical characteristic velocity .... m/s	r_f	Final port radius .... m
DAQ	Data acquisition system	$\bar{p}_c$	Average chamber pressure .... bar
G_{ox}	Oxidizer mass flux .... g/cm^2 s	$P1$	Settling chamber pressure .... bar
L_g, L	Length of fuel grain .... m	$P2$	Combustion chamber pressure .... bar
L/D	Ratio of total length to initial port diameter of fuel	$RFNA$	Red fuming nitric acid
L^*	Characteristic length .... m	X/L	Ratio of axial length to total length of fuel
m_f	Mass of fuel burnt .... g	ρ_f	Density of fuel .... kg/m^3
$\dot{m}_f$	Mass flow rate of fuel .... g/s	η	Combustion efficiency

zone formed upstream and downstream of the protrusion will also increase continuously. Kumar and Kumar [9,10] carried out numerical studies on protrusion and demonstrated that beyond some height, the protrusion are ineffective as the high temperature zone will be far removed from the fuel surface. If the burn time is large (as is the case with both the above studies), the protrusion could be effective only for a fraction of their burn time. Both these studies address the overall effect. They report that protrusions were effective for the overall burn time. If one wants to capture the time upto which a protrusion is effective, then smaller burn times are to be used. From the above arguments, it is evident that a study of the effect of protrusion should be carried out with a smaller burn time.

Protrusion till date has been used in hybrid rockets, mainly to increase the regression rate by altering the boundary layer thickness formed due to the oxidizer flow over the hybrid fuel in the combustion chamber. The protrusion has also been used to improve the combustion efficiency as it alters the flow in the combustion chamber and helps in better mixing between fuel and oxidizer. In most hybrid rocket experiments, the fuel used was either polymeric fuel, which does not form melt layer during combustion or fuel such as wax which forms melt layer during combustion. The combustion process for both the cases is completely different. The combustion of the polymeric fuel takes place within the boundary layer as explained in Refs. [14,15]. The combustion of fuel such as wax which forms melt layer during combustion, burn within the boundary layer as well as outside the boundary layer in the form of droplets, which occurs due to the shear force between melt layer and oxidizer flow. Due to the dual combustion process, combustion within boundary layer and droplet combustion outside the boundary layer, the regression rate for such type of fuels was observed to be higher [7,13].

When a protrusion is used along with a fuel which melts like wax, the improvement in the regression rate observed is marginal. The results reported by Grosse [6] for wax fuel show that the regression rate improvement is only restricted to a small region downstream of the protrusion, but overall regression rate improvement is not significant. The reason could be that the regression rate improvement in such type of fuel which forms melt layer is dominant due to the droplet combustion. Gany and Timnat [4] have reported regression rate for non-melting fuel and observed an improvement of around 50%, which is due to the reduction of overall boundary layer thickness. The reason is that the dominant combustion mechanism for a non-melting fuel is boundary layer combustion.

In this paper an effort has been made to explore the effect of the height of a single protrusion in the enhancement of regression rate and combustion efficiency or $C^\star$ efficiency. A burn time of 0.5 s was used in the current study. The fuel used for the current study is wax, which is a combination of 30% of micro-crystalline wax and 70% of paraffin wax, detail properties are given in Ref. [12]. It forms a melt layer during combustion. Due to the shear force exerted by the flow of oxidizer on the melt layer, the melt layer is sheared off into fine droplets and these droplets burn outside the boundary layer. This droplet entrainment is the dominant phenomenon for the higher regression rate in such type of fuel, whereas for non-melting fuel boundary layer combustion is the dominant phenomenon of combustion. Thus, non-melting fuel has lower regression rate. When a protrusion is placed at any location within the combustion chamber, then the boundary layer thickness is reduced some distance downstream of the protrusion. This increases the regression rate of a non-melting fuel. In the case of a melting fuel, the shear force on the fuel surface is reduced in the region surrounding the protrusion due to the existence of recirculation zones around the protrusion. This reduces the droplet entrainment. But in the region downstream of the protrusion where the flow reattaches itself and beyond, the shear force is increased due to the decrease in the boundary layer thickness. But the overall effect with the use of protrusion on regression rate is marginal as compared to the case without protrusion. When a bluff body is used in conjunction with the protrusion, the entrainment of droplet is significant as the oxidizer impinges directly on the fuel surface, thus the regression rate is also significantly high. Details are also available in Ref. [13]. The oxidizer used here is gaseous oxygen. The regression rate was obtained using a weight loss method as in Refs. [11,18]. In addition, an interrupted burning test [12,18] was used, i.e. the port was allowed to evolve during the combustion process and the combustion was stopped at regular intervals of time to measure the regression rate.

2. Experimental set up and test procedure

The experimental setup used here is similar to the one used in the previous study [12] and it is shown in Fig. 1. It consists of two oxygen cylinders mounted on a weighing balance. The mass loss of oxygen was measured with the help of a weighing balance, which had a least count of 1 g and can measure up to a maximum of 150 kg. Constant mass flow rate was obtained by allowing the oxidizer to flow through a settling chamber as shown in Fig. 1. The outlet diameter of the settling chamber was chosen such that the flow was choked. The settling chamber pressure was measured with the help of pressure transducer (P1) obtained from U V Enterprises along with a pressure indicator as shown in Fig. 1. The mass flow rate of oxidizer was calculated from the measured reduction in mass for a fixed burn time. The combustion chamber pressure (P2) was measured with the help of a piezoresistive transducer manufactured by DRUCK Ltd. UK and data was