

Effect of Activated Charcoal on the Performance of Hybrid Rocket Motor



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Abstract In the present study, attempts were made to study the effect of activated charcoal (AC) on performance of hybrid rocket motor with polyvinyl chloride–dioctyl phthalate (PVC–DOP) as solid fuel. Activated charcoal at 1, 2 and 5% mass fractions was added to PVC–DOP. The regression rate and combustion efficiency of the PVC–DOP/AC fuel combinations were determined using laboratory-scale hybrid rocket motor with gaseous oxygen as oxidizer. The results showed that among the fuel combinations studied, PVC–DOP with 1% AC exhibited the highest improvement in regression rate as well as combustion efficiency. The excessive char formation was observed as the mass fraction of AC increases and this causes the reduction in performance of hybrid rocket. Additionally, the mechanical properties were studied and TGA analysis was also conducted for the PVC–DOP/AC fuel samples.

Keywords Hybrid rocket · Regression rate · Combustion efficiency · Activated charcoal · PVC–DOP solid fuel

1 Introduction

Hybrid rocket is the combination of solid and liquid rocket engine, where the fuel and the oxidizer are stored in two different phases. Due to this distinctive feature, hybrid rocket possesses some advantages over the solid and liquid rockets. Hybrid rockets are safer, cost-effective and easier to handle during transportation. They can throttle which is not possible in solid rockets. Apart from this, since the propellant constituent is in solid phase, the complexities in designing the pump feed system are

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lesser than liquid rockets. Despite of these advantages, yet, hybrid rocket is not being used in practical applications due to its lower regression rate and poor combustion efficiency relative to solid and liquid rocket engines. Furthermore, the shift in O/F ratio with time and sliver losses are creating more complications in designing the hybrid rocket [1, 2].

In general, the polymers such as hydroxyl-terminated polybutadiene (HTPB), polyethylene (PE), polymethylmethacrylate (PMMA) and polyvinyl chloride (PVC) are frequently used as solid fuels in conventional hybrid rockets [2]. Over the past several decades, various methods [3, 4] have been developed to improve the regression rate of solid fuels in hybrid rocket motor. Some of these methods are adding energetic metals (aluminium, boron, magnesium etc.), metal hydrates and oxidizer particulates (ammonium particles) as additives to solid fuel and using different oxidizer injection techniques and creating turbulence inside the combustion chamber. Karabeyoglu [5, 6] reported that the paraffin-wax-based fuels can regress 3–5 times faster than the conventional polymeric-based fuels. However, the inherent nature of poor mechanical properties restricts the utilization of wax-based fuels in practical applications. In solid propellants, using activated charcoal as burn rate modifier is an effective method to enhance the burn rate [7]. Also, activated charcoal has been used as an additive to solid fuels in hybrid rocket research [8]. The activated charcoal enhances heat to the fuel surface through radiative heat transfer mode [2].

It has been reported in the literature that the activated charcoal is used as the burn rate enhancer in solid propellants [7]. The results showed an increase in the regression rate by 100% and the pressure index of combustion is 0.65. Following these results, it is expected that the use of activated charcoal can enhance the performance of hybrid rocket motor. Also, there is no abundant data available regarding the effect of the mass fraction of activated charcoal on performance of hybrid rocket. Thus, in the present study an attempt has been made to study the effect of activated charcoal on performance of laboratory-scale hybrid rocket with PVC–DOP as a solid fuel. Apart from this, thermal decomposition and mechanical properties of PVC–DOP/AC fuel combinations were also studied.

2 Experimental Procedures

In the present study, the combination of PVC–DOP (50:50) was used as fuel. In PVC–DOP combination, PVC is a plastisol (amorphous phase) and DOP is a plasticizer (liquid phase). Activated charcoal at 1, 2 and 5% mass fractions was added as additive to the PVC–DOP fuel. The properties of PVC–DOP/AC are given in Table 1.

Table 1 Properties of fuel constituents

Ingredient	Chemical formula	Density (kg/m ³)
PVC	C ₂₀₀₀ H ₃₀₀₀ Cl ₁₀₀₀	1380
DOP	C ₂₄ H ₃₈ O ₄	980
AC	C	2100

2.1 Preparation of Fuel Grain

In the present study, solid fuel is a combination of PVC and DOP in the ratio 50:50. Prior to blending the DOP with PVC powder, DOP should be dehumidified to remove the moisture. Then, the PVC is added to DOP and this combination is mixed using a sigma blade mixer (4 kg capacity) under ambient conditions for 3–4 h. After this, activated charcoal is added to the slurry and stirred till they blend without any lumps. Further, this slurry is used to prepare the fuel grains using mould and mandrel setup. Once the slurry is casted in the mould, it should be kept in vacuum chamber to remove the trapped air. Later, the mould is kept in the oven for curing process at 125 °C for 4 h. A well-structured grain is formed after curing. Prior to casting the fuel grains, grease was applied to avoid sticking to the mould and mandrel. The dimensions of the fuel grain are given in Table 2. Figure 1 presents X-ray photographs of the PVC fuels grains prepared in the present study. It can be observed from Fig. 2 that the fuel grain is void-free.

Table 2 Dimensions of the hybrid rocket motor

Fuel grain length	188 mm
Motor length	240 mm
Port diameter	15 mm
Outer diameter	50 mm
Throat diameter	10 mm
Exit diameter	24 mm

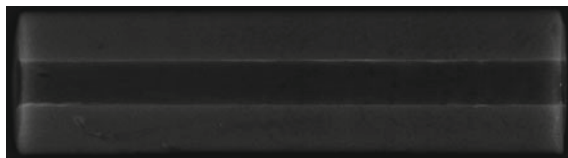


Fig. 1 X-ray photographs of PVC–DOP fuel grains

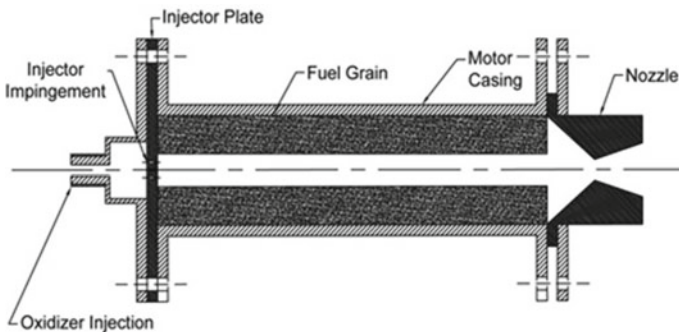


Fig. 2 Laboratory-scale hybrid rocket motor

2.2 Experimental Setup

The geometrical representation of the laboratory-scale hybrid rocket motor is shown in Fig. 2. It has shower head injector, motor case with fuel grain and C-D nozzle made of high-density graphite covered with mild steel casing. The dimensions of the motor and fuel grains are given in Table 2. The experiments on hybrid rocket motor were conducted using the experimental facility shown in Fig. 3. This experimental facility is similar to the one used in Ref. [12]. In Fig. 3, experimental setup consists of two commercially available gaseous oxygen cylinders, weighing balance, oxidizer feed system, electrical systems and test bed. The gaseous oxygen was supplied to the motor at the rate of 30 g/s. The oxidizer mass flow rate was measured by taking the weight of the oxygen cylinders before and after the combustion over the intended time. The oxidizer flow was controlled using the solenoid valve which is connected to sequential timer. This sequential timer controls the time required to open and close the solenoid valve. The ignition of the motor was achieved by igniting the solid propellant bead embedded with nichrome wire. This nichrome wire is connected to the electrical wire which is then inserted into chamber through the nozzle in such way that the propellant bead is at injector end. A 12 V DC power was supplied through the electrical wire to ignite the solid propellant bead. Once the propellant bead is ignited, the solenoid valve will open to inject the oxidizer. The entire sequence was controlled using the sequential timer.

In the current experimental study, regression rate (r) is deduced using the interrupted test in weight loss method. A detail explanation of this method can be found in Ref. [10]. In this method, the mass of the fuel (m_f) consumed during combustion

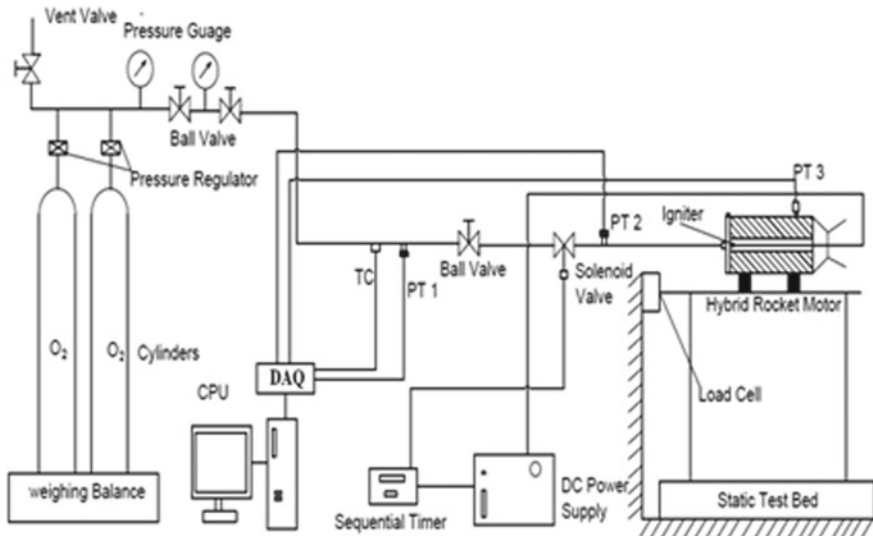


Fig. 3 Hybrid rocket experimental facility

is determined by measuring the weight of the motor before and after combustion. This mass lost in the motor will be measured at regular intervals of time (t_b) by interrupting the combustion. Using the known mass of the fuel consumed at each interval, the final diameter of the fuel grain will be measured using Eq. (1). Further, this final diameter will be helpful to calculate the regression rate and oxidizer mass flux (G_{ox}) using the Eqs. (2) and (3).

$$d_f = \sqrt{\frac{4m_f}{\pi\rho_f L} + d_i^2} \quad (1)$$

$$\dot{r} = \frac{(d_f - d_i)}{2t_b} \quad (2)$$

$$G_{ox} = \frac{\dot{m}_{ox}}{A_p} \quad (3)$$

The combustion efficiency is determined using Eq. (4). The experimental characteristic velocity (C_{ex}^*) is calculated with the help of Eq. (5). In Eq. (5) the average chamber pressure is measured using piezoresistive pressure transducer at the sampling rate of 2 kHz. This pressure transducer is connected at the nozzle end of the motor, as shown in Fig. 3. The response of pressure transducer is recorded using NI-9215 module and Lab-View signal express software. The theoretical characteristic velocity (C_{th}^*) is determined using NASA SP-2713 chemical equilibrium software [11] at corresponding chamber pressure and O/F ratio.

$$\eta = \frac{C_{ex}^*}{C_{th}^*} \quad (4)$$

$$C_{ex}^* = \frac{P_c A_t}{\dot{m}_t} \quad (5)$$

The thermal degradation studies of PVC–DOP/AC fuel formations are conducted using simultaneous thermal analyser (STA). The experiments are conducted under the nitrogen atmosphere at the heating rate of $10^\circ\text{K min}^{-1}$. In addition to this, the effect of activated charcoal on the mechanical properties of PVC–DOP fuel formations is also studied. The mechanical properties are determined using UTM-3655, INSTRON instrument at the strain rate of 5 mm/min under the ambient conditions.

3 Results and Discussions

3.1 Studies on Regression Rate

Regression rates for the PVC–DOP/AC fuel combinations were determined with the help of experimental facility shown in Fig. 3. The regression rate data reduction method is illustrated in experimental procedure section (using Eqs. 1–3). Gaseous oxygen is used as the oxidizer and its flow rate is maintained around 30 g/s for the entire experiments. In case of interrupted test method, the hybrid rocket requires a series of four interruptions during combustion with a burn time interval of 2 s. Figure 4 presents the regression rates for the fuel combinations studied in the present study. It can be seen from Fig. 4 that the regression rate is significantly enhanced compared to the PVC–DOP fuel alone. Among the PVC–DOP/AC fuel combinations, PVC–DOP/AC1% has given the better regression rates. However, there is no substantial difference observed in regression rate among the PVC–DOP/AC fuel formulations. The mass flux index for all the PVC–DOP/AC fuel formulations is less than 0.5.

In Fig. 4, the regression rate above the 90 kg/m² s is observed to be higher for the PVC–DOP/AC5% compared to other fuel combinations. As the oxidizer mass flux drops below the 90 kg/m² s, the regression rate for the PVC–DOP/AC5% decreased. The reason for this is explained as follows. After extinction of the combustion, the fuel grains were cut and the fuel surface was observed. The soot formation is observed over the fuel surface in case of all the PVC–DOP/AC fuel grains. For the PVC–DOP fuels with 2 and 5% AC mass fraction, the soot formation is much higher than with 1% AC. The cut sections of the fuel grains indicating soot layer are shown in Fig. 5 for the PVC–DOP/AC5% fuel. The soot formed might be due to the increase in the carbon content in the fuel with the addition of AC. In addition to this, the PVC itself

Fig. 4 Regression rate versus oxidizer mass flux of PVC–DOP/AC fuel formulations

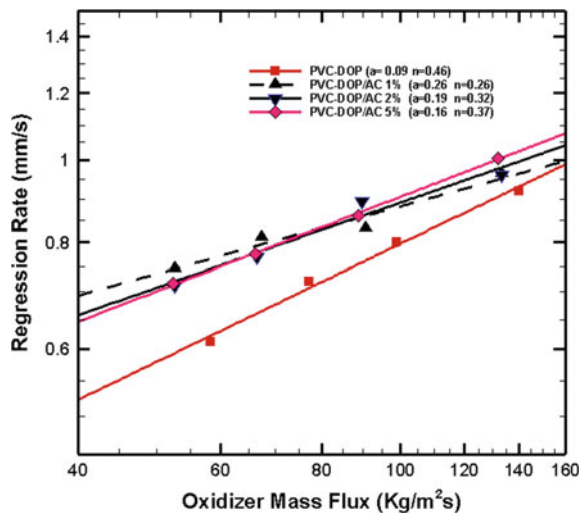
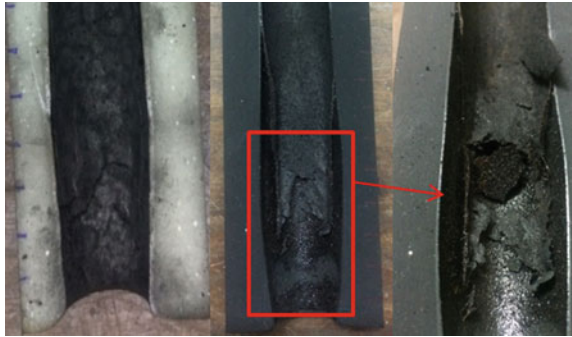


Fig. 5 Soot formation in burnt PVC–DOP fuel grains with (5% AC) and without AC



is a carbon-rich material. Hence, the soot formation is intensifying as the carbon AC mass fraction increases and more number of carbon atoms in the PVC also aids to form the more soot during combustion along with AC. This soot layer on the fuel surface acts as ablative surface which inhibits the pyrolysis process over the fuel surface. Due to this, the regression rate is decreasing with increasing AC mass fraction as the time progress during combustion. Thus, if one wants to use the AC in PVC–DOP fuels, <1% AC mass fraction is preferable.

3.2 Studies on Combustion Efficiency

In the earlier section, a significant improvement in regression rate was observed with the addition of AC to PVC–DOP. Furthermore, it would be interesting to observe the combustion efficiencies of the PVC–DOP/AC fuel formulations. Therefore, in this section experiments were carried out to study the combustion efficiencies of all the fuel formulations. The oxidizer mass flow rate is maintained at 30 g/s. The burn time for these experiments was 6 s. The pressure transducer (GE make, UNIK 5000 model) was used to record the chamber pressure through NI DAQ system. The average chamber pressure was used to calculate the experimental characteristic velocity (see Eq. 4). The combustion efficiency is determined using Eq. (5). The combustion efficiencies for the PVC–DOP/AC fuel formulation are presented in Table 3. It is given in Table 3 that the highest improvement is obtained for the PVC–DOP/AC1% fuel formulation. The improvement was around 21% compared to base

Table 3 Combustion efficiencies of PVC–DOP/AC fuel formulations

Fuel composition	O/F	η (%)
PVC–DOP	4.1	60
PVC–DOP/AC1%	2.64	73
PVC–DOP/AC2%	2.72	66
PVC–DOP/AC5%	2.6	63

Table 4 Mechanical properties of PVC–DOP/AC fuel formulations

Fuel composition	Maximum tensile strength (MPa)	Percentage elongation (%)
PVC–DOP	0.24	27.31
PVC–DOP/AC1%	0.44	25
PVC–DOP/AC2%	0.24	18.25
PVC–DOP/AC5%	0.11	14.5

fuel. The decrease in combustion efficiency is observed with increase in AC mass fraction in PVC–DOP. This might be due to the soot formation as shown in Fig. 5.

3.3 Studies on Mechanical Properties

In this section, the effect of addition of activated charcoal on mechanical properties of PVC–DOP fuel is investigated. The mechanical properties such as tensile strength and percentage elongation are determined using INSTRON UTM-3655 instrument at 5 mm/min strain rate. The mechanical properties for the PVC–DOP/AC fuel samples are given in Table 4. It is observed from Table 4 that the mechanical properties are decreasing with increasing AC mass fraction in PVC–DOP fuel. It is also seen that at higher AC mass fraction the mechanical properties were significantly dropped and it was around two times lower than the origin fuel. Among the PVC–DOP/AC fuels, the percentage elongation for the PVC–DOP/AC1% is 25% and it is within the range (6–25%) that required to be used in practical applications [12].

3.4 TGA/DTG Studies

It was realized from the above studies that the PVC–DOP/AC1% is best fuel among the PVC–DOP/AC formulations. Thus, an attempt has been made to observe the degradation behaviour of the PVC–DOP/AC1% fuel sample using TGA/DTG curves. The TGA and DTG for the PVC–DOP and PVC–DOP/AC1% fuel formulation are presented in Figs. 6 and 7.

It can be seen from Fig. 6 that the degradation takes place at two different steps. The first step corresponds to the degradation of the DOP and the second step corresponds to PVC. The peak degradation temperatures at two steps are indicated on DTG curves in Fig. 7. The peak temperature for pure PVC is around 298 °C. With the addition of 1% AC the peak degradation temperature of PVC reduced significantly and it was around 272 °C. Thus, the addition of AC significantly increases the regression rate of PVC–DOP (see Fig. 4).

The temperature ranges and mass loss are given in Table 5 for the corresponding TGA curves in Fig. 5. From Table 5 it can be observed that the phase change of the

Fig. 6 TGA curves for PVC–DOP/AC fuel formulations

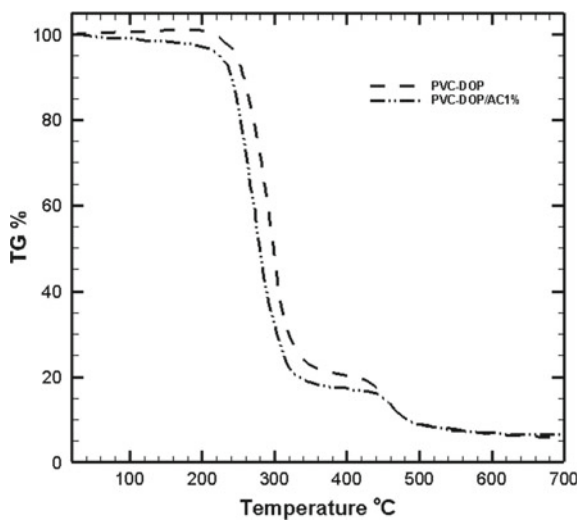


Fig. 7 DTG curves for PVC–DOP/AC fuel formulations

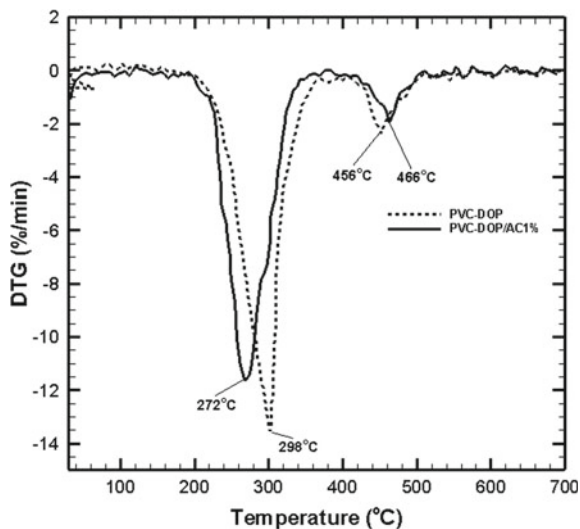


Table 5 TGA results for the PVC–DOP/AC fuel formulations

Fuel sample	T _{S1} (°C)	M ₁ (%)	T _{S2} (°C)	M ₂ (%)	M _R (%)
PVC–DOP	205–380	80	380–698	14	6
PVC–DOP/AC1%	180–358	76	358–699	11	12

PVC started earlier (at 180 °C) with the addition of 1% AC. However, the residual mass at 700 °C is higher for the PVC–DOP/AC1% fuel. This might be due to the soot left after total degradation of the fuel sample. It has been already described earlier that the soot formation is the reason for decrease in regression at higher mass fractions of AC in PVC–DOP fuels. This residual mass may be increased further with the increase of AC mass fraction.

4 Conclusions

The effect of activated charcoal on regression rate and combustion efficiency of the PVC–DOP-based polymeric fuel was investigated. Activated charcoal was added to the solid fuel at 1, 2 and 5% mass fractions. Additionally, mechanical properties and thermal characterization for these fuel formulations were also studied. The important conclusions from the current study are as follows:

1. The addition of activated charcoal enhances the regression rate by around 25% compared to pure PVC–DOP fuel.
2. At lower oxidizer mass flux, the regression rate for PVC–DOP/AC1% is better than other fuel combinations.
3. The formation of excess soot during combustion resulted in decrease in the regression rate with increase in AC mass fraction.
4. The combustion efficiency for the PVC–DOP/AC1% is higher among PVC–DOP/AC fuel formulations. This improvement was around 25% greater than the PVC–DOP alone.
5. The mechanical properties decreased with increasing AC mass fraction in PVC–DOP.

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