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Combustion Studies of Aluminized PVC Plastisol

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The combustion behavior of a cylindrical port burning polyvinyl chloride plastisol hybrid fuel grain in an oxidizing stream of gaseous oxygen has been studied. The effect of aluminum metal powder on the regression of the hybrid fuel has been investigated over a wide range of loading from 2 to 45% at varying oxidizer flow rates and combustion chamber pressures. The regression rates have been found to be higher for aluminized fuels; however, increasing metal loading has been found to yield decreasing regression rates. An empirical relationship has been obtained between the metal loading and the regression rate of the fuel. The average regression rate and mass consumption rate of the fuel have been correlated with the oxidizer flow rate and initial oxidizer mass flux.

Nomenclature

A,B,C = empirical constants
d_t = throat diameter of the nozzle, mm
d_p = port diameter of the fuel grain, mm
G = total mass flux, g/cm^{2}s
G_{oi} = initial oxidizer mass flux, g/cm^{2}s
L = length of the fuel grain, cm
M = mass fraction of the aluminum metal in the aluminized plastisol
M_{max} = mass fraction of the aluminum metal in the aluminized plastisol at which the regression rate is maximum
$\dot{m}_f$ = rate of fuel mass consumption, g/s
$\dot{m}_o$ = rate of oxidizer mass flow, g/s
n = exponent
p_c = combustion chamber pressure, kg/cm^2
p_j = injection pressure, kg/cm^2
$\dot{r}$ = average fuel regression rate, mm/s

Introduction

METAL additives have long been used as a means of improving the performance of solid- and liquid-propellant rockets by virtue of higher flame temperature, and it has been established that a broad spectrum of internal ballistic characteristics can be achieved by inclusion of metals.

The regression of the hybrid fuel is governed by the heat transfer to the regressing surface from the flame zone, on the one hand, and the effective heat of gasification on the other. Particles in the flame zone are envisaged to contribute substantially to heat transfer rates due to their high emissivity, besides enhancing the flame temperature itself. Obviously, inclusion of metal powders in the fuel grain has been taken in its natural course by the pioneer researchers in the field to enhance the fuel regression rate and to improve the performance of the hybrid propellant motor.

Much work has been done in the past to investigate the effect of various metal powders and metallic compounds,[1-7] as well as the size, shape and form[8] of the combustion behavior of the hybrid propellant system, both analytically and experimentally. Favorable results have indicated that a very high percentage of metal powders could be employed[4,5] for various improvement aspects.

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Polyvinyl chloride (PVC) has been used extensively as a fuel in composite solid propellants in addition to the variety of application areas in different plastic industries, by virtue of its easy availability and low cost. PVC plastisols, processed with the plasticizer dibutyl phthalate (DBP) have been found to have very good mechanical and chemical properties. During the earlier combustion studies with this plastisol, it was observed to yield regression rates comparable with other fuels under identical oxidizer flow rates.

The present investigation is aimed to find out the suitability of aluminum metal powder in conjunction with PVC plastisol hybrid fuel. Combustion studies have been carried out with cylindrical port burning PVC plastisol fuel grain in the stream of gaseous oxygen with varying percentage of metal powder loading at fixed and varied oxidizer mass flow rates. The effect of metal additive has been investigated on the average regression rate and the fuel mass consumption rate of the hybrid fuel.

Experimental Setup and Test Procedure

The investigation has been conducted on a head end injection hybrid test motor loaded with fuel grains with a length of 18 cm, outside diameter of 50 mm, and port diameter of 20 mm. Gaseous oxygen was supplied from commercial high-pressure cylinders through an injector having nine 1.5-mm-diam orifices. The experimental setup used was the same as in Ref. 9. A pyrotechnic igniter with an ignition delay of 0.2 s was used to initiate combustion. All the tests were conducted for a fixed duration of combustion of 10 s.

Pure and aluminized PVC plastisol fuel grains were prepared by the usual process of mixing, casting, and curing. Various percentages of aluminum metal power, that is, 2, 5, 7, 10, 15, 20, 30, 40, and 45% by weight, were incorporated in

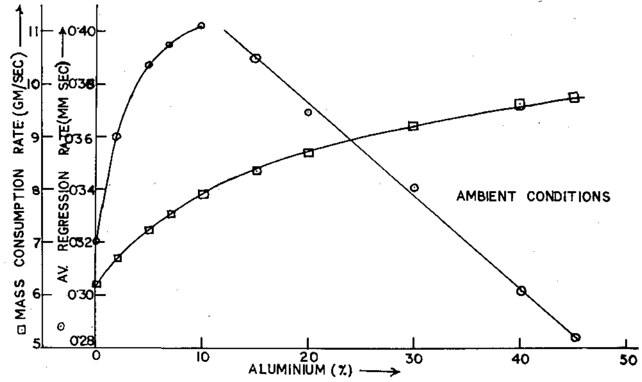

Fig. 1 Effect of aluminum on average regression rate and mass consumption rate at ambient conditions.

the PVC plastisol for making different grains. It was not possible to include a greater quantity than 45% of aluminum because of the inability of the mixer blades to rotate due to the excessive viscosity of the mix.

Two series of experiments have been carried out. In one, a constant injection pressure of 20.4 kg/cm^2 was employed for all percentages of aluminized PVC plastisol. The investigation was carried out without a nozzle and with a nozzle of 10.5 mm throat diameter. The oxidizer mass flow rate was found to be 28.62 ± 0.5 gm/s when the combustion chamber pressure was recorded at 5.80 ± 0.3 kg/cm^2 (with the nozzle), while the flow rate was 34.62 ± 0.5 gm/s at ambient pressure (without the nozzle). In the other series, oxygen was injected at varying injection pressures from 13.6 to 47.6 kg/cm^2 for 20 and 40% aluminized plastisols and regression rate data were collected separately for test motors without a nozzle and with a nozzle of 10.5 mm throat diameter.

Local regression rates along the length of the fuel grain at an interval of 1 cm were determined by accurately measuring the unburnt web thickness with a micrometer (least count = 0.001 mm). The fuel grain was accurately weighed before and after the test and the mass consumption rate was determined by the difference of weights, assuming a constant rate of consumption. The average regression rate was computed from the weight loss and average port diameter during each test.

Results and Discussion

Figure 1 presents the variation of average regression rate and fuel mass consumption rate for aluminized PVC plastisols of various percentage metal loading at ambient conditions. It is observed that with the increase of aluminum loading, the regression rate values increase to a certain percentage loading at which the regression rate is maximum, however, decreasing regression rate values are obtained with higher percentage loading of the metal. The result is as per expectation, because initially the addition of aluminum would increase the flame temperature and, thus, the heat flux at the regressing fuel surface would also increase, resulting in a higher regression rate. However, at a constant oxidizer mass flow rate, the flame temperature would increase up to a certain percentage of aluminum loading only, and a higher percentage of aluminum than this would not be effective in raising the flame temperature because of the lack of sufficient oxygen in the flame zone. Also, due to the increase of the number of aluminum particles in the flame zone, the aluminum would remain unburnt or partially burnt resulting in a decrease of the flame temperature.

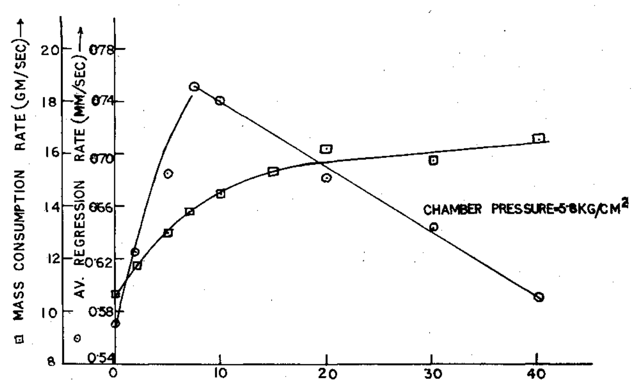

Fig. 2 Effect of aluminum on average regression rate and mass consumption rate at pressure burning.

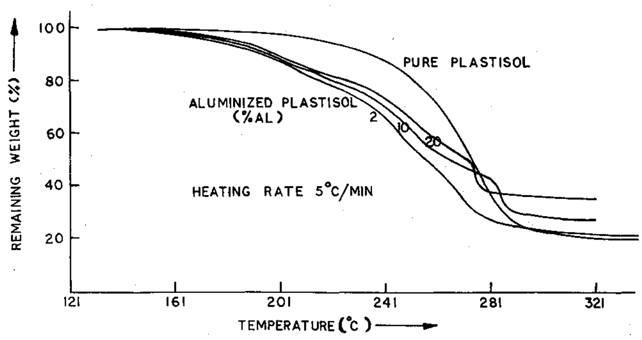

Fig. 3 TG curve of pure and aluminized PVC plastisols.

The overall experimental oxidizer-to-fuel ratio (O/F) is sufficiently higher than the stoichiometric ratio in all percentages of aluminized plastisol. However, it decreases from the experimental ratio of 5.6 for virgin plastisol to 3.55 for 40% aluminized plastisol as compared to stoichiometric values of 1.46 and 0.998, respectively. All the same, the oxidizer concentration in the flame zone is governed by the diffusion of the oxidizer from the freestream to the combustion zone. The diffusion of oxygen to flame zone, in turn, suffers higher restriction with the increase of percentage of aluminum loading due to the formation of nonvolatile combustion products of aluminum. Also, higher percentage aluminized plastisol would result in higher percentage of nonvolatile oxide and unreacted metal particles in the flame zone. These particulates would carry away the heat from the flame zone resulting in decrease of heat flux available at the regressing surface. The increase of thermal conductivity of the fuel with increasing percentage of aluminum loading may be taken as another factor responsible for decreasing the regression rate.

The following empirical relationship for average rergression rate was found to fit in the results obtained in the present investigation for higher percentages of aluminum loading:

$$\bar{r} = AM_{\max}^{n} - B(M - M_{\max})$$

Substituting the values of A, B, and n in the above expression, we have

$$\bar{r} = 0.48\, M_{\max}^{0.075} - 0.345\,(M - M_{\max})$$

For lower percentages of aluminum loading, the second term is not included, and a relationship between mass fraction of aluminum and the average regression rate may be written:

$$\bar{r} = 0.48\, M^{0.075}$$

Figure 2 presents the variation of average regression rate and fuel mass consumption rate for aluminized PVC plastisols of various percentage metal loading at a combustion chamber pressure of 5.8 kg/cm^2 and oxidizer mass flow rate of 26.86 gm/s. The curves have a similar trend as those of Fig. 1, however, the regression rate values are higher for the plastisols burning at a chamber pressure. This is in line with the pressure flow dependence of hybrid regression rates.[10]

On examination of the percentage of aluminum loading in PVC plastisol fuel grain at which the maximum regression rate is obtained, it is observed (from Figs. 1 and 2) that it shifts from 12% aluminum loading at ambient pressure to 8% loading for a combustion chamber pressure of 5.8 kg/cm^2. Comparison of the point of inflection in these two figures in this manner may point towards a misleading conclusion. In fact, the higher combustion chamber pressure depicted in results plotted in Fig. 2 results in a reduced oxidizer mass flow rate and hence an overall O/F ratio than the ambient combustion case, as the injection pressure has been maintained constant in these two cases. The resulting point of inflection obtained at a lower percentage of aluminum loading in Fig. 2 thus becomes obvious, and a higher percentage than this would result in an increased percentage of particulate combustion products, enhanced restriction to diffusion of oxygen from freestream to flame zone, and a lower O/F ratio—in turn, yielding a lower regression rate.

To investigate the interaction of aluminum with the ingredients of PVC plastisol, some thermogravimetric analyses were carried out separately and the results have been plotted in Fig. 3. The thermogravimetric (TG) curves clearly show that although the degradation of PVC resin is retarded in the presence of aluminum, loading of aluminum in a small percentage in PVC plastisol accelerates the degradation markedly. Increased percentage of aluminum loading in PVC plastisol, however, results in decreased percentage of degradation. These results suggest that at least one more degradation mechanism is active in the initial range of temperature in the presence of aluminum. A detailed analysis (communicated in a separate investigation) of the reaction mechanism indicates that it is mainly an interaction between the HCl gas evolved during the degradation of PVC resin and the DBP plasticizer in the presence of aluminum, and not between HCl gas and aluminum.

In the case of degradation studies in a low temperature regime, aluminum enhances the degradation rate but does not get consumed. On the other hand, in the case of the combustion process, aluminum itself takes active part in combustion besides enhancing the degradation rate. The observed trend of variation of mass consumption rate of the aluminized plastisols in Figs. 1 and 2, therefore, is as per expectation.

The fuel mass consumption rate is found to increase with increasing loading of metal powder. The aluminized plastisol with increased percentages of metal loading have increasing fuel density, which is mainly responsible for the increase of fuel mass consumption rate with the metal loading.

The values of average regression rate of 20 and 40% aluminized PVC plastisol for different oxidizer mass flux have been plotted in Fig. 4. The average regression rate value is found to increase with increasing oxidizer mass flux and the observed exponential variation of regression rate with oxidizer mass flux may be related by the following empirical relationship in both the cases:

$$\bar{r} = 0.091\ G_{oi}^{0.5}$$

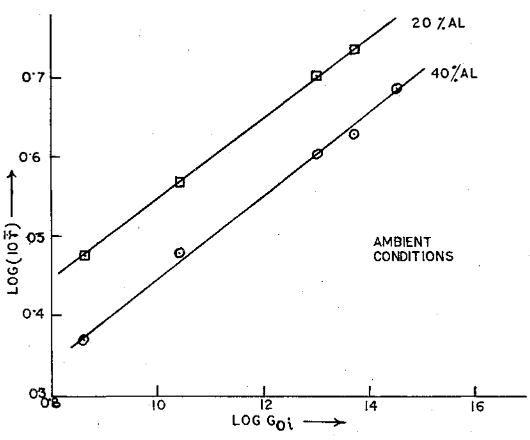

Fig. 4 Average regression rate as a function of oxidizer mass flux.

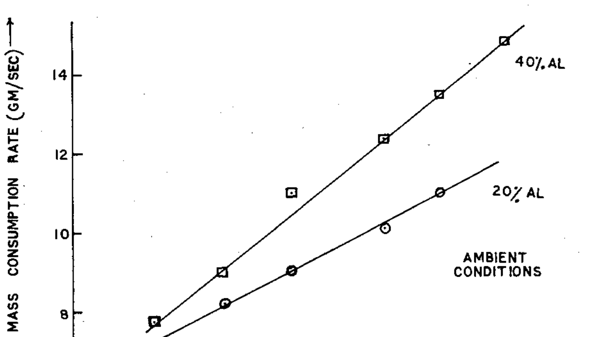

Fig. 5 Mass consumption rate as a function of oxidizer mass flux at ambient conditions.

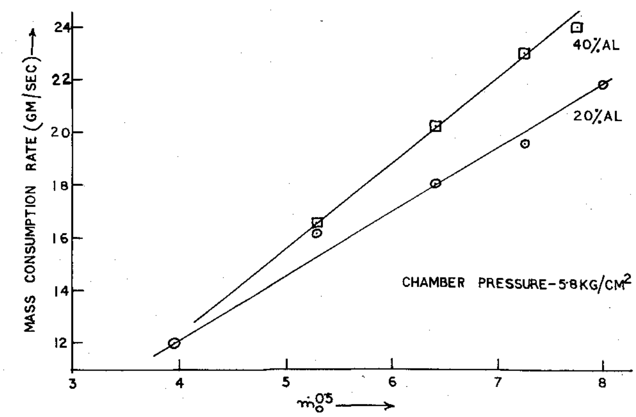

Fig. 6 Mass consumption rate as a function of oxidizer mass flux at pressure burning.

At the same time, the 20% aluminized plastisol has been found to invariably result in a higher regression rate than the 40% one for a given oxidizer mass flux. Aluminum loading beyond a given percentage is apt to decrease the flame temperature as well as the available heat flux at the regressing surface, as has been discussed earlier.

The values of mass consumption rate of 20 and 40% aluminized PVC plastisol for different mass flow rates have been plotted in Figs. 5 and 6 for the fuel burning at ambient conditions and at 5.8 kg/cm² combustion chamber pressure, respectively. The mass consumption rate of both the aluminized plastisols have been found to increase exponentially with the oxidizer flow rate and the following empirical relationship may be established:

$$\dot{m}_f = C\dot{m}_o^{\ 0.5}$$

The empirical constant C has been found to depend both on percentage metal loading and combustion chamber pressure. The 20 and 40% aluminized plastisol are found to yield a value of 1.30 and 1.64, respectively, for the constant, for the fuel burning at ambient conditions, and 2.14 and 3.28, respectively, for the fuel burning at a combustion chamber pressure of 5.8 kg/cm².

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