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Self-disintegration Effects on the Regression Rate of Composite Polymer Particle Paraffin Fuel (CM3PF)

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Abstract
Self-disintegration is a new concept to increase the regression rate of hybrid propulsion fuels. The new fuel concept consists of fuel unit and functional binder as a lock unit. When the functional binder is unlocked at some critical condition, the fuel charge will be disintegrated into small fractions near regression surface. A fuel model -composite polymer particle paraffin fuel (CM3PF) was demonstrated the concept, in which paraffin was selected as the functional binder whose unlocked critical condition is melting temperature, and another is granular polymer fuel. The combustion performance and the regression rate of CM3PF were studied in different composite conditions and at different Oxygen flux in experiment. The results show a few of granular polymer fuels escape from regression surface into flow phase. The regression rate tendencies of CM3PF are same as pure paraffin fuel, but their regression rate is higher than paraffin at 5%, 10% and 15% (wt) of Φ0.850mm～1.000mm granular polymer fuel. The experimental results obtained verify that the new concept is useful to increase the regression rate.

1. Introduction

High regression rate of solid fuel is required by solid-gas or solid-liquid hybrid propulsion. Paraffin-based and HTPB -based fuels are conventional solid fuels for hybrid propulsion, but poor mechanical properties of paraffin fuels and low regression rate of HTPB fuels should be improved. Some technologies have been used to improve the regression rate of HTPB-based fuels. Nano-metal (Al, Mg, Al/Mg and AlH_3), Carbon, AP and gun powder are useful additives to improve the regression rate of HTPB-based and Paraffin-based fuel [1~5], but the improvements are not enough to meet the high regression rate requirements of hybrid propulsion at high charge density. How to improve regression rate by 10 or 100 orders of magnitude is a big problem. Consolidated charge with propellant grains [6] is a good idea, since consolidated charge will break into small block grains to enlarge the burning surface of propellant charges in high pressure and combustion. The concept of "self-disintegration" is a possible way to improve regression rate, according to the principle of consolidated charge. "Self-disintegration" is a new concept of hybrid propulsion fuel to increase the regression rate. The new fuel concept consists of fuel unit and functional binder as a lock unit. When the functional binder is unlocked at some critical condition, the fuel charge will be disintegrated into small fractions or grains near the regression surface. A fuel model -composite polymer particle paraffin fuel (CM3PF) will be designed to demonstrate the concept by experiment, in which paraffin was selected as the functional binder whose unlocked critical condition is melting temperature, and another is granular polymer fuel.

2. Experiment

2.1 Tested Samples

Tested samples are made from microcrystalline wax (90# paraffin) and polystyrene grains (D301) by casting technology. 90# paraffin properties are: specific heat 1073.66 J/kg K, combustion heat 46.19 kJ/g, melting point

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72.2℃, density 0.927g/cm^3. D301 polystyrene properties are: combustion heat 28.74 kJ/g, density 1.15g/cm^3, granularity (φ 0.315 mm - φ 1.25 mm)⩾95%. The granularity of polystyrene (PS) is separated into different granularity groups: S group (φ 0.60 mm～φ 0.71 mm) and B group (φ 0.85 mm～φ 1.00 mm). The formulations and properties of the tested composite samples are shown in Table 1.

Table 1: Formulations of CM3PF (mass %)

composite	1#	2#	3#	4#	5#	6#
90# paraffin	95	90	85	95	90	85
PS grain	5(B)	10(B)	15(B)	5(S)	10(S)	15(S)
density (g/cm^3)	0.926	0.906	0.891	0.886	0.882	0.876
specific heat (J/kg K)	1094.40	1073.61	902.21	1170.75	984.52	965.65
combustion heat (kJ/g)	44.81	44.39	43.39	45.59	45.12	43.83

CM3PF fuels were casted into a steel tube with 30mm length, 19mm external diameter and 25mm diameter, and keep a φ=4 mm centre hole in charge. A tested sample is shown in Figure 1.

Figure 1: A CM3PF tested sample with the B/KNO_3 igniting charge

2.2 Experimental set

The experimental set was designed in according to the combustion chamber set of the space propulsion lab at Politecnico di Milano in Figure 2.

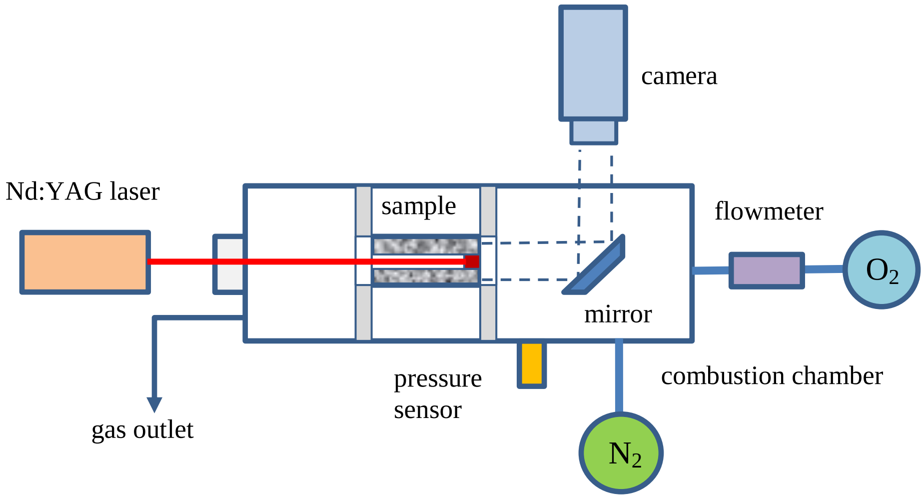

Figure 2: Experimental set to test regression rate of CM3PF

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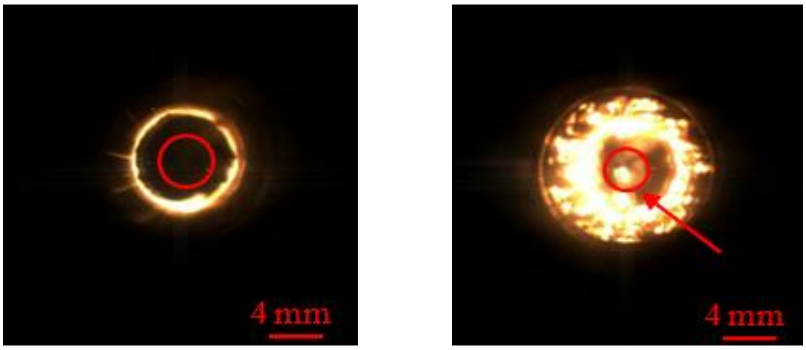
The combustion pressure is controlled by nitrogen and oxygen sources, the flux of oxygen flow is controlled by a digital mass flow meter, and combustion images in cross section are record by a high-speed camera. Fuel charge is ignited by a free-running Nd:YAG pulsed laser, in which the igniting charge is a B/KNO_3 composite.

3. Result and Discussion

The combustion process of CM3PF was compared with 90# paraffin at 380 $kg/cm^2/s$ oxygen flux and 1MPa pressure in Figure 3. The combustion images were taken at 3.5 s after ignition. The paraffin flame is clear and simple, while the CM3PF flame is more complex and stronger than paraffin flame. A lot of burning grains are sprayed out from the burning surface into the gas flow.



(a) 90# paraffin (b) CM3PF

Figure 3: Combustion images of CM3PF and 90# pure paraffin at 3.5 s after ignition

The phenomenon is illustrated in Figure 4. When paraffin melts at melting point, the bound polymer grains are free and escape from the regressing surface into the gas flow zone. The total escaped mass of CM3PF from the regressing surface is more than only the paraffin fuel.

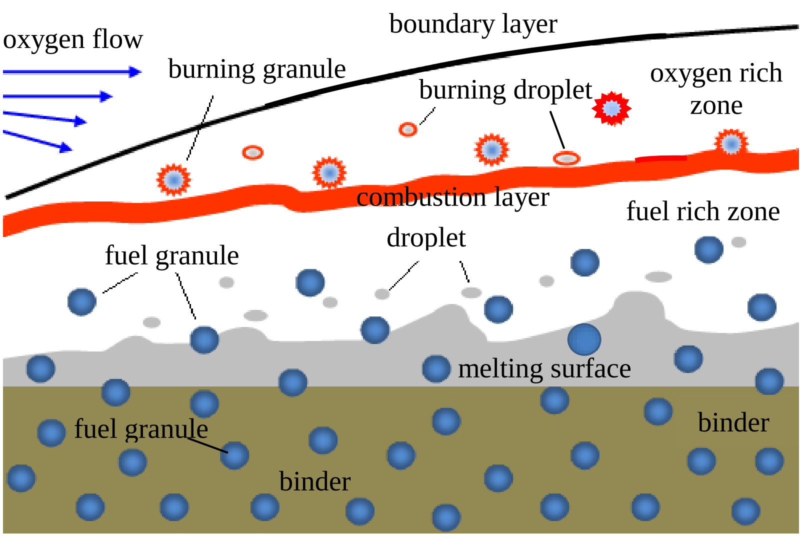


Figure 4: Disintegration process of CM3PF

The mass regression rate of CM3PF consists of paraffin rate and polymer grain rate,

$$\dot{m} = (1-\emptyset)\dot{m}_{paraffin} + \emptyset\dot{m}_{polymer} \quad (1)$$

$$\dot{m}_{polymer} = r_{unlock}\rho_{polymer} \quad (2)$$

Where, $\emptyset$ is the volume fraction of polymer grain, $\dot{m}_{paraffin}$ is mass rate of paraffin, $\dot{m}_{polymer}$ is mass rate of polymer grain and r_{unlock} is the disintegration rate. $\dot{m}_{polymer}$ depends on the "unlocking" condition, in which melting point is unlocking condition of CM3PF and r_{unlock} is the propagation rate of the melting wave.

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The regression rates of CM3PF at different oxygen mass fluxes and 1 MPa chamber pressure are shown in Figure 5. Solid line and dashed line denote regression rates by real-time process ($d(D)/d(t)$) and fitting process ($r = aG^n$) for experimental data respectively. Experimental results show that the regression rate of CM3PF is higher than 90# paraffin except for 95/5 CM3PF (1# , 4#) over 150 kg/(m^2.s) of oxygen mass flux. The result verifies that the "Self-disintegration" concept is correct and useful.

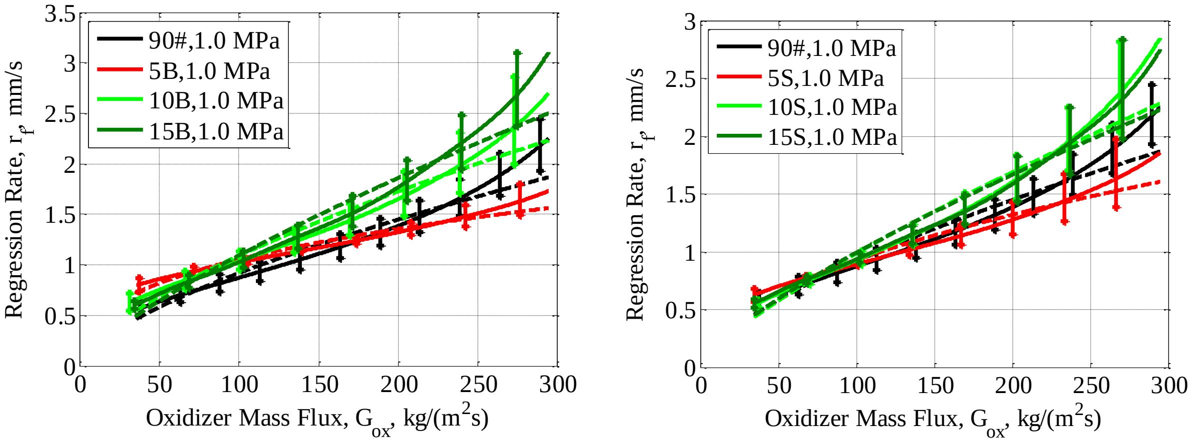
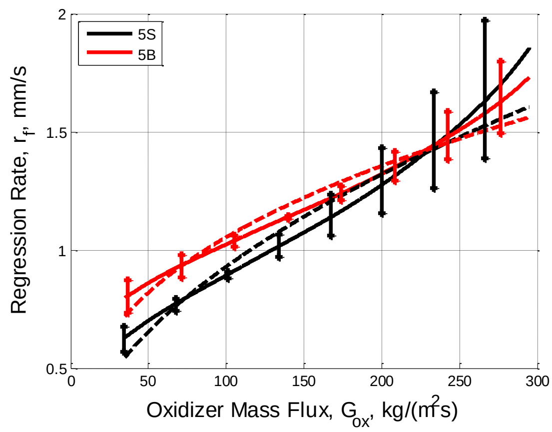
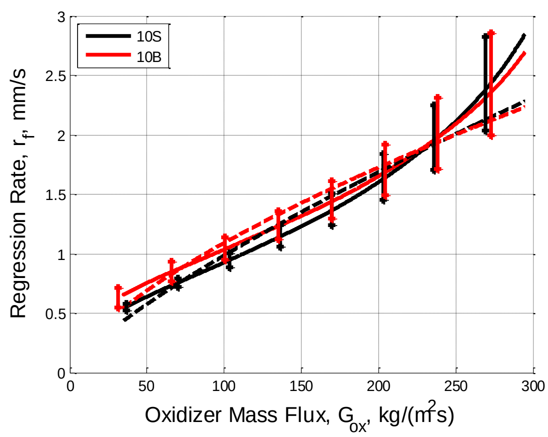


Figure 5: Regression rates of CM3PF at 5%, 10% and 15% granular polymer and 90# pure paraffin

Experimental results also show that large sizes of polymer grain is more efficient to improve regression rates than small sizes; see Figure 6. A possible cause is that large polymer grains will carry away more mass or volume from the regression surface when they escape from the fuel charge condensed phase into the gas flow.



(a) regression rate of 5% S and 5% B CM3PF



(b) regression rate of 10% S and 10% B CM3PF

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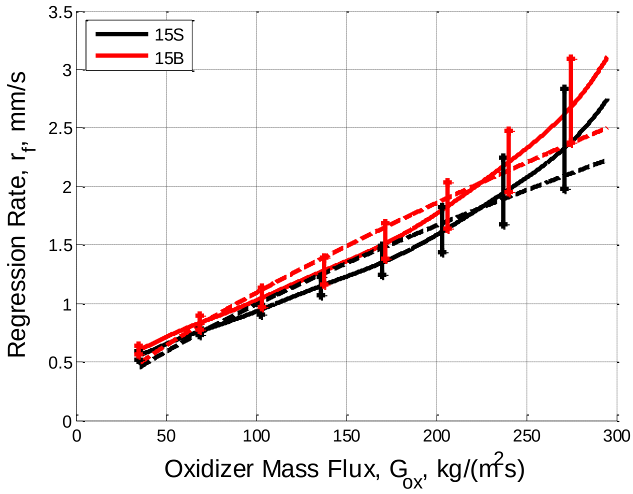

(c) regression rate of 15% S and 15% B CM3PF

Figure 6 CM3PF regression rate for large sizes and small sizes of polymer grains

4. Conclusion

CM3PF is a model to verify “self-disintegration” idea to improve regression ate of fuel. 90#Paraffin-D301PS polymer granular composite fuels are designed at paraffin /D301 PS: 95/5, 90/10 and 85/15 and granularity of PS :S group (φ 0.60 mm～φ 0.71 mm) and B group (φ 0.85 mm～φ 1.00 mm) . Combustion visualization shows a lot of burning polymer granular escape from the burning surface into the gas flow. Experimental results also show that the regression rates of CM3PF are higher than their binder, 90# paraffin. Big size of PS granular is more efficient than small size of PS granular. Experimental results prove that the “self-disintegration” concept is established.

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