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A new combustion phenomenon: penetrative combustion of 3D printed fuel grain for hybrid rocket engine

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Abstract
Traditional hybrid rocket fuel can improve fuel combustion efficiency through structural design which is conducive to aerodynamic enhancement of regression rate. However, complex structure increases the difficulty of fuel structure forming, hindering the scientific research and engineering application verification of fuel charge with heterogeneous and topological structure in the hybrid rocket. 3D printing is used to manufacture hybrid rocket fuel grains with a special mesh structure to improve combustion performance. When analyzing the gas-phase and solid-phase combustion characteristics of acrylonitrile-butadiene-styrene (ABS) fuel with a single-hole mesh structure, the penetrative combustion phenomenon of 3D printed structural fuel was first discovered, and the minimum print infill density of fuel charge axisymmetric ring disintegration caused by penetrative combustion was determined. The results show that penetrative combustion can effectively increase the regression rate.

1. Introduction

Hybrid propulsion has great application prospects in space missions such as satellite launch, space travel, orbital maneuver, planet landing and attitude control because of its high safety, low cost, reusable engine and good environmental protection [1-4]. However, the development of hybrid propulsion technology has long been restricted by low combustion efficiency and low fuel regression rate [5]. Combustion efficiency can be improved by optimizing engine structure, adding supplementary combustion chambers, etc. However, how to effectively improve fuel regression rate has always been a key issue in solid-liquid hybrid propulsion technology. At the same time, the performance and structure of the fuel cylinder manufactured by the traditional manufacturing method are relatively simple, the structure of the fuel cylinder is limited and the manufacturing process is complex, which cannot flexibly achieve rapid manufacturing, which seriously affects the rapid large-scale production of the fuel cylinder with complex geometry. 3D printing technology breaks through the traditional production mode of mixed rocket fuel propellant, and can efficiently produce fuel propellant with a variety of space complex gradient structures, which solves the problem of loading, but also increases the propellant regression rate [6-10]. M. Creech et al. used a special 3D printer to print the paraffin fuel powder column by melting deposition and conducted ignition experiments, which verified the possibility that the 3D printer could print high-energy propellant [11]. Bisin et al. printed PLA, ABS and nylon into spiral fuel grain and embedded them into paraffin matrix to form fuel grain, which increased its mechanical properties [12]. Wang et al. used ABS as a spiral structural frame to provide mechanical support for paraffin-based fuel and made a new fuel grain. Compared with paraffin-based fuel, the regression rate and combustion efficiency of this fuel is increased to a certain extent [13]. Zhang et al. studied a new composite rocket fuel propellant column composed of 3D printed ABS spiral substrate and embedded paraffin-based fuel, and designed two swirling jet injectors with opposite injection directions to spray oxygen as oxidant. The new composite fuel propellant column showed excellent combustion performance in tests. The regression rate of composite fuel was significantly increased [14]. In this paper, ABS and paraffin were chosen, ABS and ABS/paraffin fuel grains were manufactured by fused deposition 3D printing, and their internal structures were photographed using μCT. Combustion experiments were conducted using gaseous oxygen as the oxidizer at a pressure of 1 MPa, and higher regression rate was obtained.

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2. Experimental set

2.1 Fuel grain manufacturing

In this study, the standard configuration of the fuel grain is 30 mm in length (L), 16 mm in outer diameter (OD), and 4.6 mm in central hole diameter (ID), which was fabricated by fused deposition modeling 3D printing with infill densities of 60%, 70%, 80%, 90%, and 100%, and a solid ABS fabricated by cutting, as shown in Figure 1. For the ABS/paraffin fuel grain, paraffin wax with a melting point of 58°C was used to fill the ABS fuel grain with an infill density of 60%, 70% and 80%. Due to the small and dense pores of the ABS fuel grains and the obvious shrinkage of paraffin grains during the curing process, direct casting of paraffin particles into the ABS fuel grain will cause two problems, (1) paraffin particles will not uniformly occupy all the pores of the ABS fuel grain, resulting in uneven densities of the composite fuel; (2) the surface of the directly cured paraffin particles will produce very serious denting, as well as internal fracture problems may occur. ABS/paraffin fuel grains were prepared by the following method. First, the solid paraffin particles were loaded into a beaker and the beaker was placed in a water bath with the temperature set to 95°C to completely melt the solid paraffin particles into a liquid. Then the printed ABS fuel grains were put into the beaker with paraffin liquid and the water bath was maintained at 95°C for about 1h. Then the temperature of the water bath was adjusted to 63°C. When the temperature of the water bath reached 63°C, the beaker was taken out and put into the constant temperature oven, and the temperature of the constant temperature oven was set to 48°C for about 24h, so that the composite fuel grains were cured and formed.

Figure 1. Solid,100%,90%,80%,70%,60%ABS fuel grain.

2.2 Combustion experimental setup

The combustion experimental setup was modified and built based on the design of the combustion test setup in the Space Propulsion Laboratory (SPLab), Politecnico di Milano, Italy, as shown in Figure 2. The gas supply system includes an air compressed pump, oxygen, and nitrogen. The purpose of incoming air is used for pre-stamping and saving nitrogen. Nitrogen provides the required pressure for the combustion chamber as well as terminates the combustion of the fuel grain. Gaseous oxygen (Gox) is used as the oxidizer. The oxygen flow control system uses a Bronkhorst F202 high-precision flow controller produced in the Netherlands and the oxygen mass flow rate is 3 g/s. The pressure control system includes four solenoid valves, a control instrument, and a pressure sensor to ensure that the combustion chamber is in a 1 MPa quasi-steady state during the combustion experiment. Laser radiation ignition is used in this experiment. A Nd^{2+}:YAG solid-state pulsed laser with a wavelength of 1064 nm was used as the radiation source to ignite the B/KNO3 ignition composition at the center hole of the fuel grain, thus igniting the inner surface of the fuel grain. The combustion image is reflected by a 45°-mounted plane mirror and then recorded by a high-speed camera at 500 fps/s.

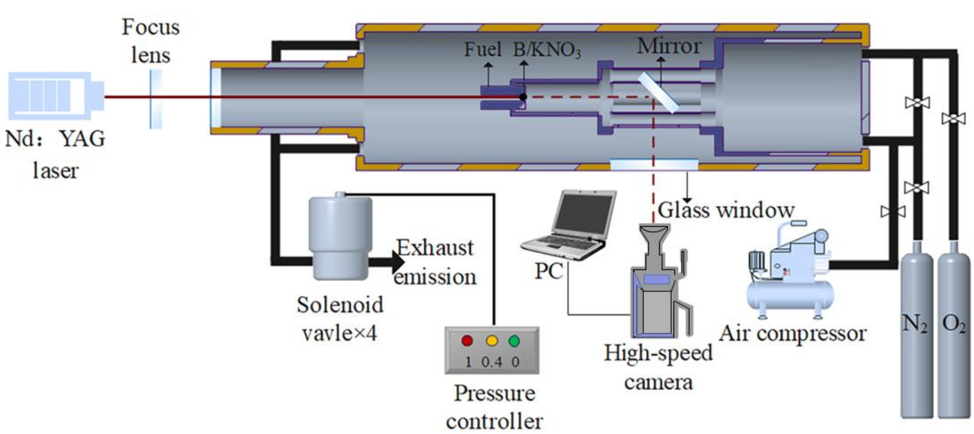

Figure 2. 2D radial hybrid combustion test setup

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The masses of the fuel grains were weighed before and after the experiment to obtain the mass difference ΔM. The burn time t_b was obtained from the video taken by high-speed photography. The relationship between the average recession rate $\overline{r}_f$ and the change in the diameter of the combustion surface port is:

$$\overline{r}_f = (D_1 - D_0)/2t_b \tag{1}$$

where D_0 is the initial port diameter before combustion, and in this study, D_0 = 4.6 mm. The value of the final port diameter D_1 after fuel combustion is estimated from the mass of fuel consumed during combustion as follows:

$$D_1 = \sqrt{{D_0}^2 + \frac{4}{\pi} \cdot \frac{\Delta M}{\rho_f L}} \tag{2}$$

where L is the length of the fuel grain. ρ_f is the solid fuel density:

$$\rho_f = \rho_{ABS}\omega_{ABS} + \rho_{\text{paraffin}}\omega_{\text{paraffin}} \tag{3}$$

where ω is the percentage of the total mass of the substance, $\bar{D}$ is the arithmetic mean of the initial and final diameters of the port, and the mean diameter is $\bar{D} = (D_1 + D_0)/2$. The relationship between the average mass flux $\bar{G}$ and the average oxygen mass flow rate $\overline{m}_{ox}$ can be expressed as:

$$\bar{G} = \frac{\overline{m}_{ox}}{\pi \bar{D}^2/4} \tag{4}$$

3. Result and discussion

3.1 Combustion test of ABS

Figure 3 shows the microstructure images of solid ABS and 100% ABS taken by a 3D high-resolution μCT technique. The comparison shows that, based on the current development of 3D printing technology, the printed sample will have fine pores even if the infill density is turned up to the maximum. This allows a portion of oxygen to pass through the interior of the fuel grain, accelerating the oxygen flow rate on the fuel combustion surface, increasing convective and radiative heat transfer, and thus increasing the regression rate. We call this phenomenon Penetration Combustion (Penecom). The regression rate vs. Gox is shown in Fig. 4(a), and the growth rate of regression rate vs. Gox is shown in Fig. 4(b). Table 1 shows the regression rates for Solid, 100% and 90% ABS fuel grains, and percentage increase of regression rate compared to Solid ABS for 100% and 90% ABS fuel grains. At an oxygen mass flux of 80 $\mathrm{kg/(m^2 \cdot s)}$, the regression rates of 100% and 90% ABS fuel grains were increased by 22.6% and 32.7%, respectively.

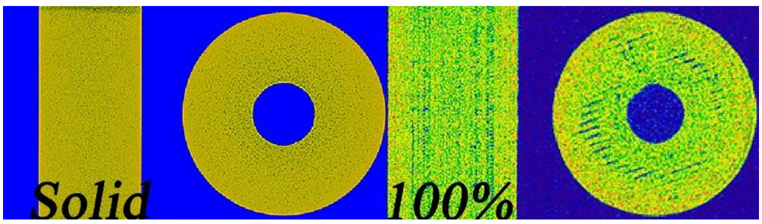

Figure 3. Microstructure images of solid ABS and 100% ABS by μCT

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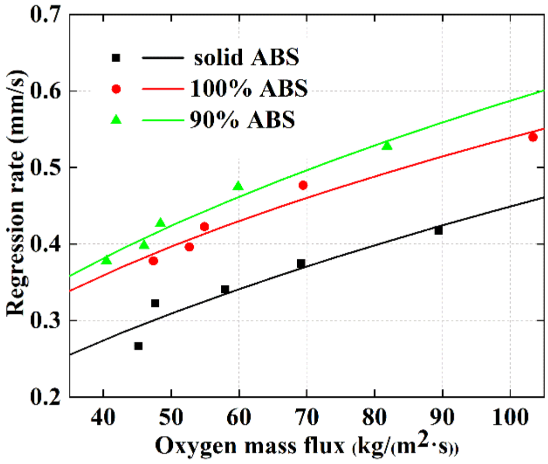
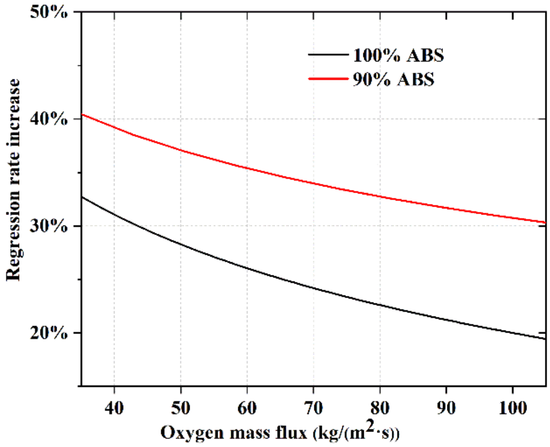


a)



b)

Figure 4. a) regression rate vs. Gox, b) growth rate of regression rate vs. Gox

Table 1: Regression rates for Solid, 100% and 90% ABS fuel grains, and percentage increase of regression rate compared to Solid ABS for 100% and 90% ABS fuel grains

(Gox=80 $kg/(m^2 \cdot s)$)	$\overline{r}_f$(mm/s)	Δr_f(%)
Solid ABS	0.398	-
100% ABS	0.488	22.6
90% ABS	0.528	32.7

For ABS fuel grains with infill densities of 60%, 70% and 80%, due to their relatively large internal pores and high convective and radiative heat transfer, combustion of the fuel occurs from the inside, forming a distinct circle that causes the fuel grain to fracture from the circle, as in Figure 5. The combustion state of ABS fuel grains is recorded as t_i at the start of combustion and taken as $t_i + 0.2s$, $t_i + 0.4s$ and $t_i + 0.6s$. Although this increases the regression rate, it also decreases the combustion efficiency.

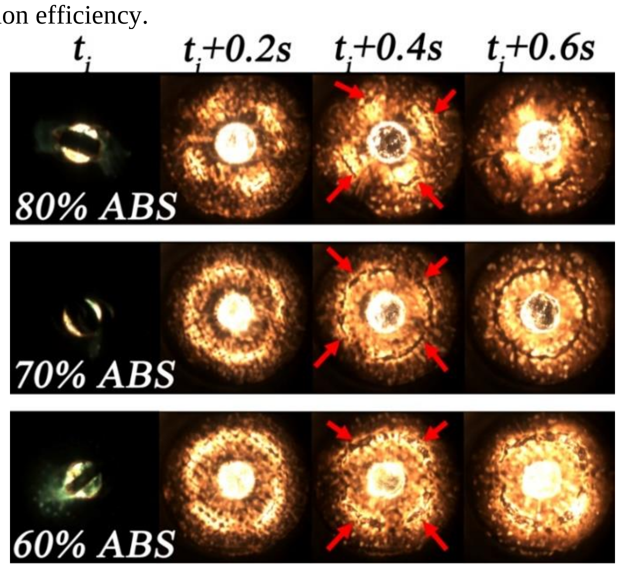


Figure 5. Combustion of 80%, 70%, and 60%ABS fuel grain.

3.2 Combustion test of ABS/paraffin

In order to keep the combustion from creating a fracture, we filled paraffin wax into the interior of the porous ABS fuel grains. In order to clearly determine whether the prepared ABS/paraffin composite fuel grain is uniformly filled with paraffin and whether the composite fuel grain is dense, μCT was used to take a microstructure picture of the

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interior of the fuel grain as shown in Figure 6. It can be observed from Figure 6 that there are almost no pores in both top and main views, and the paraffin fills all the original pores with only a few extremely small "dots", but overall, it does not affect the subsequent experiments, indicating that the ABS/paraffin composite fuel preparation method is reliable and can be used for combustion experiments.

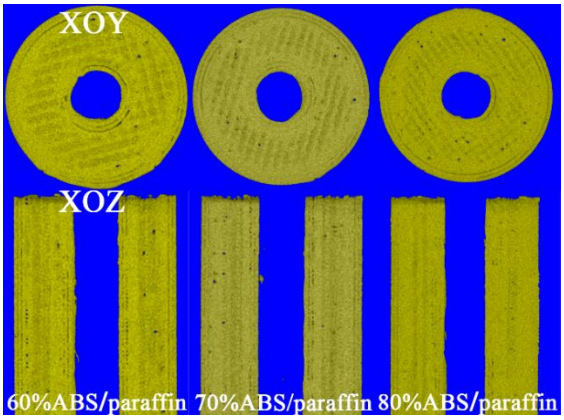

Figure 6. Microstructure images of 60%,70%,80% ABS/paraffin by μCT.

Figure 7 shows the regression process of the end face of ABS/paraffin fuel grains during combustion, and it can be observed that many small droplets splashed out around the center hole, and the higher the content of paraffin, the more obvious this phenomenon is. This is due to the fact that when the ABS/paraffin fuel starts to burn, the temperature inside the combustion chamber rises rapidly and the melting point of paraffin is only 58°C. Therefore, the paraffin preferentially starts to melt and form droplets, which splash out under the rapid blowing of the oxygen flow. It is logical that the higher the temperature, the faster the paraffin melts and the faster the regression rate.

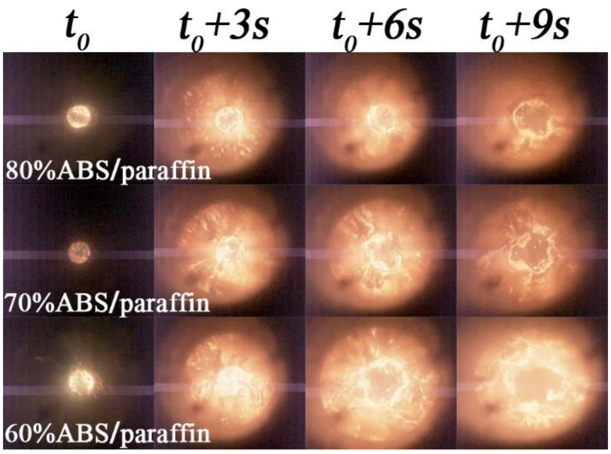

Figure 7. Combustion of 80%, 70%, and 60%ABS/paraffin fuel grain.

Figure 8 shows the regression rate versus oxygen mass flux for 100% ABS, 80% ABS/paraffin, 70% ABS/paraffin and 60% ABS/paraffin fuel grains. As can be seen in Figure 8, the regression rate of pure ABS fuel grain increases more slowly with increasing oxygen mass flux, while the regression rate of the three ABS/paraffin fuels increases more rapidly with increasing oxygen mass flux. After the combustion starts, the temperature in the combustion chamber rises rapidly to about 3000°C. The solid paraffin particles melt rapidly and sputter out with the oxygen airflow. On the one hand, the combustion of paraffin increases the receding rate, and on the other hand, the sputtering of paraffin causes the combustion surface area of ABS fuel to increase, so that the penetration combustion can start, which makes the pyrolysis rate of the compound fuel increase greatly, so the overall regression rate increases rapidly. The regression rate curve of 100%ABS fuel grains was excluded, and the comparison between the three ABS/paraffin composite fuel grains showed that the regression rate of the ABS/paraffin fuel grains increased with the increase of oxygen mass flux, and the regression rate of ABS fuel grains with low infill density and high paraffin content was faster. Table 2 shows the regression rates for 80%, 70% and 60% ABS/paraffin fuel grains, and percentage increase of regression rate compared to Solid ABS for 80%, 70% and 60% ABS/paraffin fuel grains. At an oxygen mass flow rate of 80 $kg/(m^2 \cdot s)$, the regression rates of 80%, 70% and 60% ABS/paraffin fuel grains were increased by 44.3%, 63.2% and 84.8%, respectively.

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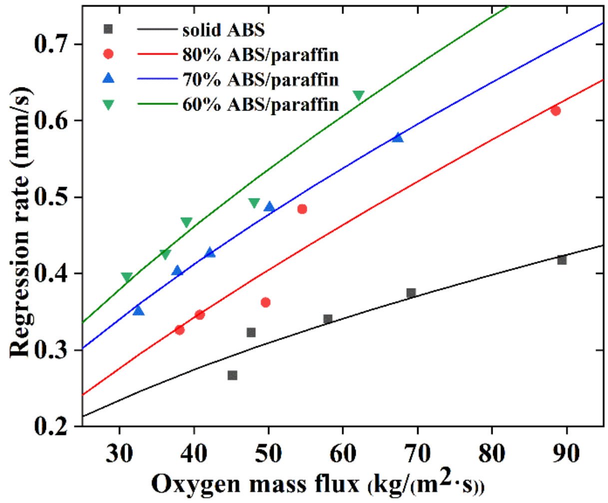

Figure 8. Regression rate vs. Gox of solid ABS, 80%, 70%, and 60%ABS/paraffin fuel grain.

Table 2: Regression rates for 80%, 70% and 60% ABS/paraffin fuel grains, and percentage increase of regression rate compared to Solid ABS for 80%, 70% and 60% ABS/paraffin fuel grains

(Gox=80 $kg/(m^2 \cdot s)$)	$\overline{r}_f$(mm/s)	Δr_f(%)
80%ABS/paraffin	0.574	44.3
70%ABS/paraffin	0.650	63.2
60%ABS/paraffin	0.736	84.8

4. Conclusion

In the study of ABS fuel grains with different infill densities, a combustion phenomenon was found in which oxygen can flow inside the fuel charge and combustion occurs inside the fuel grain, which we call penetration combustion. The experimental results showed that at Gox $= 80\text{kg}/(\text{m}^2 \cdot \text{s})$, the regression rates of 100% and 90% ABS fuel grains were increased by 22.6% and 32.7%, respectively. When the infill density is below 80%, the fuel grain will burn internally first, resulting in fracture, and paraffin will be filled into the fuel grain. The results of ABS/paraffin combustion show that at Gox $= 80\text{kg}/(\text{m}^2 \cdot \text{s})$, the regression rates of 80%, 70% and 60% ABS/paraffin fuel grains are increased by 44.3%, 63.2% and 84.8%, respectively. Only small-scale experimental tests have been conducted, and future work will have to consider larger-scale combustion experiments to verify its feasibility.

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