The Verifications and Demonstrations of Self-disintegration Fuel Concept for Hybrid Propulsion

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ABSTRACT

Self-disintegration concept is an innovation idea to enhance the regression rate of hybrid propulsion fuels. The self-disintegration fuel consists of fuel particles and functional locking binder. When the binder is unlocked in structure of charge at a critical condition, the fuel charge will be disintegrated into small particles to enlarge the fuel surface. The binder is an important component, and HTPB is convenient binder, but its molecular bond in chain is strong. The functional binders of weaken bond HTPB was designed and processed. The performance of weaken bond HTPB fuels were analyzed in experiments. The experimental results shown that the self-disintegrated effects of weaken bond HTPB induce the increase of regression rates.

1. Introduction

The Self-disintegration fuel Concept was putted forward early [1] as the fourth type of hybrid propulsion fuels of Paraffin based, HTPH based, Paraffin-HTPB based composited and Self-disintegration fuels (SDFs). The ideas of self-disintegration fuel concept were inspired by the consolidated gun propellant [2, 3] and R. Shen's early work [4]. A basic principle of SDF combustion is shown by the combustion of Composite Polymer Particle Paraffin Fuel (CM3PF) in Fig.1, which is a validation model of SDF concept. The fuel was composited by polyethylene particles and paraffin binder in the validation model, in which the binder is a smart temperature binder. When the paraffin binder melts at over the melting point, the force between the binder and fuel particles will be weaken to release the fuel particles from the surface of CM3PF charge in Fig 2.
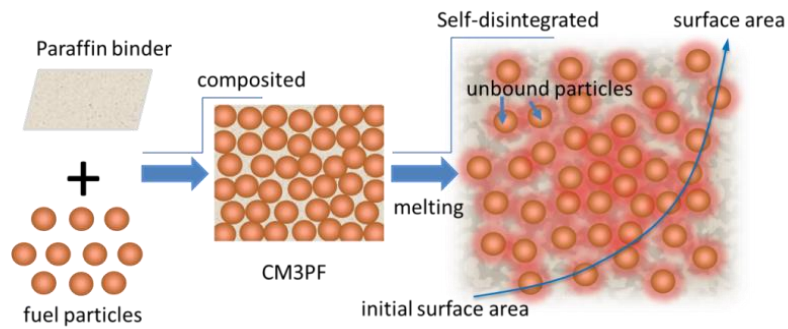
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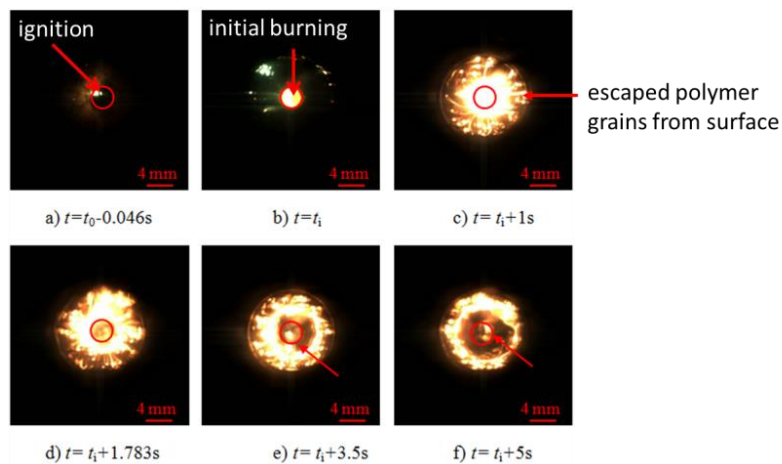Figure 1: Principle of the self-disintegration fuel

Figure 2: Escaped Fuel particles from the self-disintegration composited fuel

SDFs consist of binder and fuel particles (or fuel grains). The binder captures the fuel particles, but it will release the fuel particles at some condition, such as temperature. Carbon, carbon nanotubes, metal fibers, and foaming agent are used to modify the thermal property and the structure of binder. Another way is selecting smart binder, such as weak bond HTPB that will decompose at low temperature. The fuel particles have high combustion heat, and they will protect from stuck by melting binder, so a functional coating layer is often required, such as gas generating materials to blow fuel particles and/or surface acting material to isolate between fuel particle and binder. Modification ways show in Fig. 3.
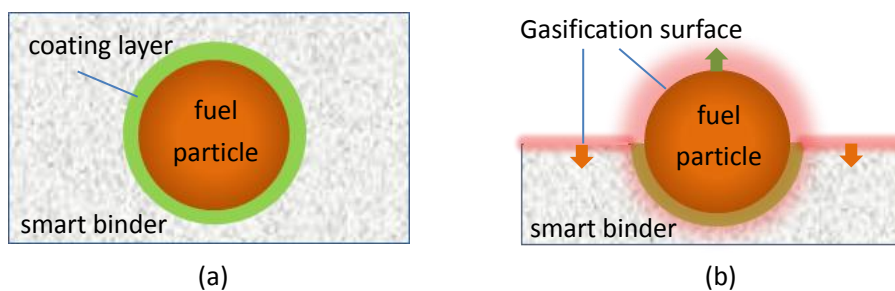

Figure 3: Modification ways of SDFs. (a) structure of SDFs, (b) gasification process of SDFs.

Many works were tried to verify the self-disintegration fuel Concept [5] in the modified paraffin-based fuels [6-9] and HTPB-based fuels [10-12]. The experimental results shown the self-disintegration concept is established, in which the regression rates of the self-disintegration fuels increase than pure paraffin and pure HTPB in some conditions. However three problems should be resolved, that are the fuel particles with high heat value, the smart binders with high mechanical performance and the combustion theory of SDFs. In the paper, the verification of SDFs concept will be down by the weaken bond HTPB fuels.

2. Weaken bond HTPB fuels

Because of the strong molecular bond energy of C-C and C-O in HTPB chain, the decomposition temperature or ignition temperature of HTPB in air condition (773K) is so high that HTPB cannot burn easily. The conventional coupling agent of HTPB is toluene diisocyanate (TDI) or isophorone diisocyanate (IPDI). We hope to find new coupling agents that can form weak molecular bonds with HTPB functional groups (-OH) to replace TDI and IPDI. The principle of weaken bond HTPB is shown in Fig. 4. The weak linking bond of molecular chain likes a smart switch. When temperature rise to a critical temperature, the smart switch will turn on or the linking bond will broke, so the functional HTPB will decompose to molecular fragments. The effect will induce high regression rate of fuel at low temperature.
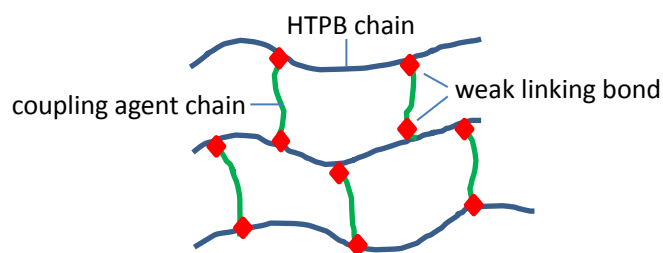

Figure 4: Molecular chain of weaken bond HTPB

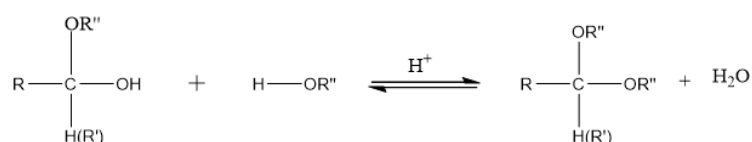The possible way is aldol reaction between hydroxy group (-OH) of HTPB and aldehyde group (-CHO) of aldehydes to form weaken ether linkage (-C-O-C-). Glutaraldehyde (GA) is one of possible aldehydes to get weaken bond linking with HTPB. Two stages of aldol reaction, half aldol reaction and the full aldol reaction , are in the aldol reaction in Fig.5.
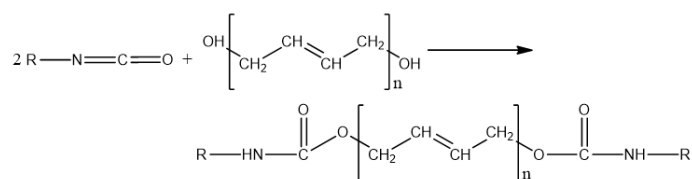
(a)   Reaction of IPDI with HTPB
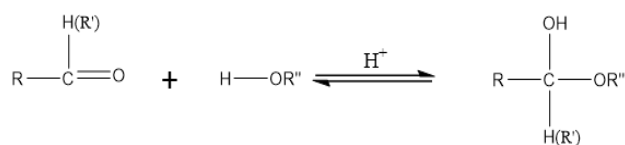
(b)   half aldol reaction

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(c) full aldol reaction

Figure 5: Aldol reaction between hydroxy group (-OH) of HTPB and aldehyde group (-CHO) of aldehydes

The basic formulation of HTPB (or conventional HTPB, HTPB+IPDI) consists of HTPB, diisooctyl adipate (DOA), isophorone diisocyanate (IPDI) and dibutyltin dilaurate (TIN), and the weaken bond HTPB formulation (HTPB+glutaraldehyde) consists of HTPB and glutaraldehyde (GA). The formulations of fuels are shown in Tab.1 and the reacted samples show in Fig.6.

Table 1: Formulations of conventional and modified HTPB fuels (wt%)

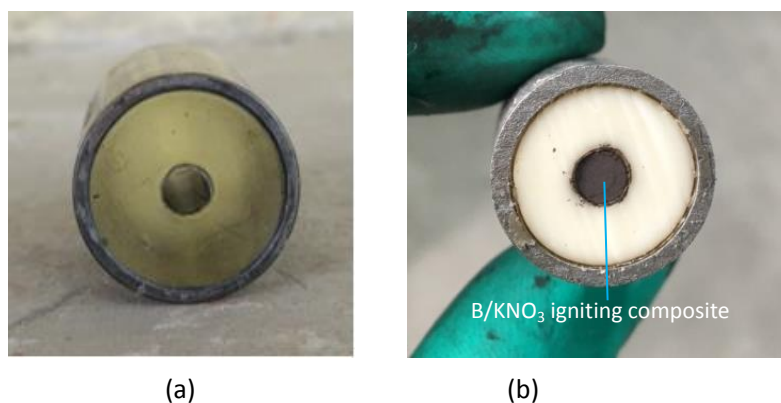| Formulation	HTPB	DOA	IPDI	TIN	GA	HCl
Conventional HTPB	78.86	13.04	7.67	0.43	0	0
Weaken bond HTPB	86.7	0	0	0	10	3.3

(a)   (b)

Figure 6: Samples of conventional HTPB (a) and weaken bond HTPB (b)

The fuels were analyzed by NETZSCH 499 at the conditions, 10mg sample, 30mL/min air flow, 10K/min temperature rate. Compared thermal analysis (DSC and TG) of HTPB+IPDI (conventional HTPB) with HTPB+Glutaraldehyde (weaken bond HTPB), the weaken bond HTPB will decomposed at lower temperature than conventional HTPB in Fig.8. The weaken bond HTPB will decompose at $101℃$-$138℃$ initially, and loss weight is about 2.47%, but the conventional HTPB decomposes at $320℃$. The initial decomposition temperature of the weaken bond HTPB is lower conventional HTPB about $219℃$, so that the regression rate of the weaken bond HTPB maybe is higher than conventional HTPB in some conditions.
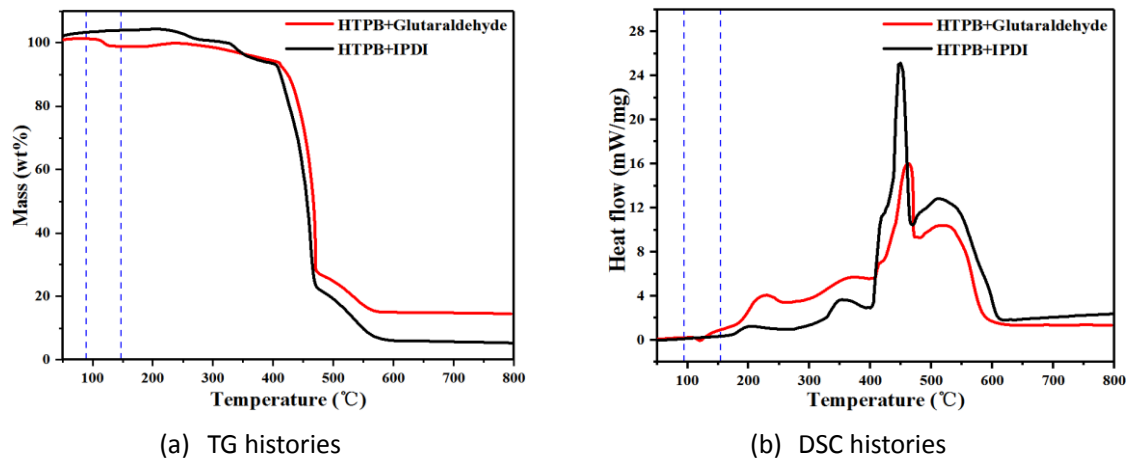
(a) TG histories

(b) DSC histories

Figure 8: Thermal analysis of conventional HTPB and weaken bond HTPB

3 Performance of HTPB fuels

3.1 Regression rate testing set

The combustion experimental set was designed on the base of experimental set of Space Propulsion Laboratory, Politecnico di Milano [13, 14, 15] in Fig.7. The operating pressure was 1 MPa. The fuels particle had the size of OD 16 mm $\times$ ID 4 mm $\times$ length 30 mm and was placed at the oxygen inlet. Air was supplied to the combustion chamber by an air compressor before combustion. The combustion chamber was pressurized to 1 MPa by nitrogen and air. Gaseous nitrogen kept the chamber pressure under the desired pressure and ejected the combustion gas out of the chamber when fuels burn. The mass flow rate of oxygen was controlled at 5 g/s by Bronkhorst F202 mass flowmeter. The pressure control system, including a pressure transducer, four solenoid valves, and four electromagnetic relays, kept the combustion chamber in quasi-steady state at 1 MPa. A laser was used to activate the B/KNO$_3$ (40/60) charge, placed upstream of the fuel particle port, and thus ignited the inner surface of the fuel particle under an oxygen flow. The high-speed camera recorded the regression process of the inner burning surface of fuel particles at 1500 fps/s, thanks to a 45 $\circ$ plane mirror reflection.
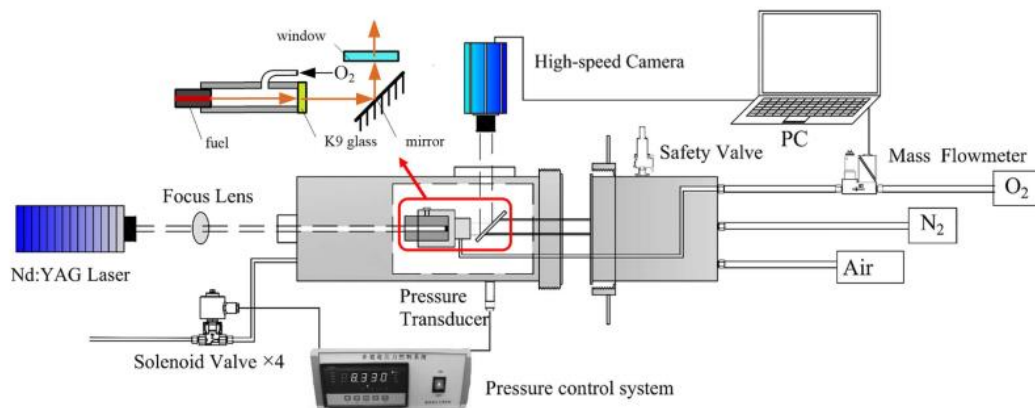

Figure 7: Experimental set to test regression rate at different pressure and oxygen flux

The high-speed photographs were processed to *(D₁ - D₀) - t* after calibration; D_1 was the instantaneous diameter of internal combustion surface at time *t*, and D_0 was the initial internal diameter of fuel particles. The detailed data processing method is based on SPLab time-resolved procedure. The discrete $(D_1 - D_0) - t$ values obtained this way were fitted as

$$D_1 + D_0 = at^n \tag{1}$$

The regression rate $\dot{r}_f(t)$ of fuels at time t was calculated as

$$\dot{r}_f(t) = (1/2)d(D_1 - D_2)/dt \tag{2}$$

The oxygen mass flow rate was measured by

$$G_{ox}(t) = 4m_{ox}/\pi D_1^2 \tag{3}$$

Then, $\dot{r}_f(t) - t$ and $G_{ox}(t) - t$ can be translated into $\dot{r}_f(t)$ vs. $G_{ox}(t)$. The mass burning rate of the central port fuel particles can be expressed as

$$\dot{m}_f(t) = A_b \dot{r}_f(t)\rho_f \tag{4}$$

For the comparison of regression rates between different solid fuels, the classical average regression rate empirical formula [16, 17, 18] of Eq. (5) for hybrid rocket motors is used:

$$\dot{m}_f(t) = a_1 G_{ox}(t)^{n_1} \tag{5}$$

3.2 Performances of HTPB fuels

The regression rates of the weaken bond HTPB and the conventional HTPB were tested by the combustion experimental set (Fig.7). The regression rates of HTPB+GA and HTPB+IPDI, and the growth rate of regression rate of HTPB+GA to HTPB+IPDI are shown in Fig.8.
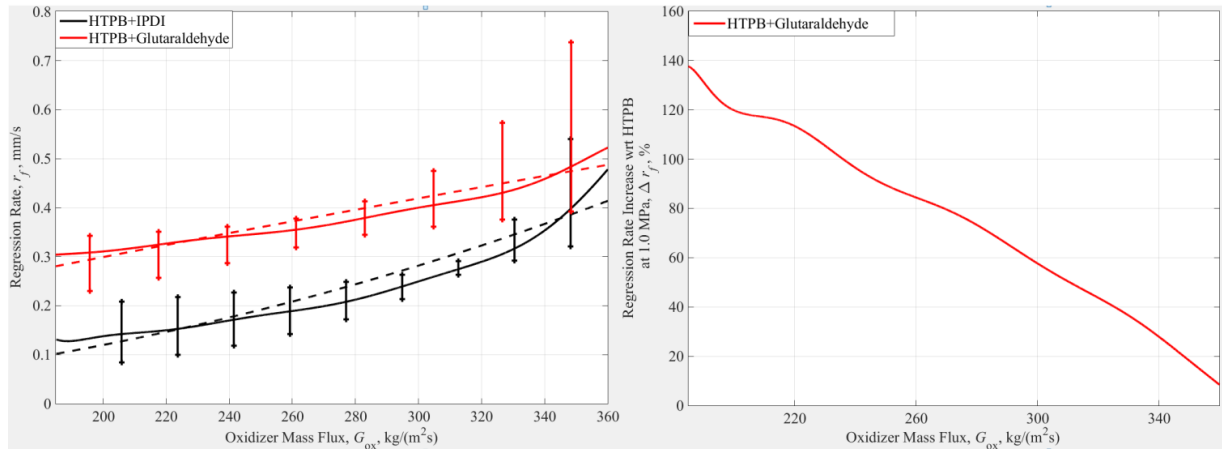

Figure 8: Regression rate of HTPB+GA and its growing value to HTPB+IPDI

The density of weaken bond HTPB and conventional HTPB are 0.921 and 0.922g/cm^3 respectively. Comparing the conventional HTPB, the weaken bond HTPB reinforce the instantaneous regression rate by 20% at *Gox* = 350 kg/m^2 s and 120% at *Gox* = 200 kg/m^2 s, respectively, as shown in Figure 8 and Tab.2. The weaken bond HTPB shows higher regression rate than conventional HTPB. However, different from the conventional burning rate additives, the percent increase in the regression rate of weaken bond HTPB gradually increases as the *Gox* decreases. Experimental results verified that aldehyde is possible substitute of IPDI as coupling agent of HTPB to get weaken linking bond with HTPB.

Table 2: Δr_f increase and fitting results of r_f / G_{ox} curves for HTPB fuels

Formula	Δr_f at 350 kg/(m²·s)	Δr_f at 200 kg/(m²·s)	G_{ox} Range from 150 to 310 kg/m²·s	R^2
HTPB+IPDI	-	-	$\dot{r}_f = (1.52 * 10^{-4})G_{ox}^{1.279}$	0.993
HTPB+GA	20%	120%	$\dot{r}_f = (1.75 * 10^{-2})G_{ox}^{0.544}$	0.971

The combustion processes of conventional HTPB and weaken bond HTPB are shown in Fig.9 and Fig.10. Comparing the combustion images of HTPB+IPDI and HTPB+GA, the regression process of HTPB+GA (weaken bond HTPB) is different from pure HTPB grain. The combustion surface of HTPB+IPDI (conventional HTPB) is clear and regresses from surface to the inside of fuel grain, but HTPB+GA surface will collapse and blow out due to softening and melting of grain, that is similar to the regression of paraffin grain.
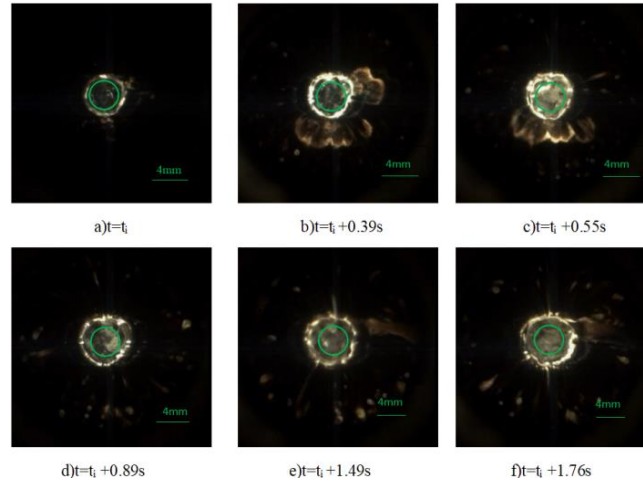

a)t=t_i b)t=t_i +0.39s   c)t=t_i +0.55s

d)t=t_i +0.89s   e)t=t_i +1.49s   f)t=t_i +1.76s

Figure 9: Combustion images of HTPB+IPDI grain (conventional HTPB) at different combustion time

a)t=t_i b)t=t_i +0.46s   c)t=t_i +0.98s

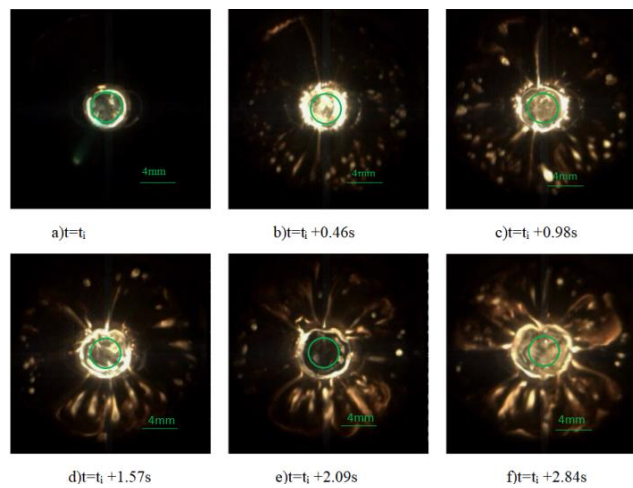d)t=t_i +1.57s   e)t=t_i +2.09s   f)t=t_i +2.84s

Figure 10: Combustion images of HTPB+GA grain (weaken bond HTPB) at different combustion time

4. Conclusion

HTPB fuel is a good fuel except for low regression rate. If HTPB is used as binder of SDFs, its regression rate should be improved. Weaken bond modification maybe is a good way to improve HTPB combustion performance. The possible way is aldol reaction between hydroxy group (-OH) of HTPB and aldehyde group (-CHO) of aldehydes to form weaken ether linkage (-C-O-C-). Glutaraldehyde (GA) is one of possible aldehydes to get weaken bond linking with HTPB. Thermal analysis results shown HTPB+ Glutaraldehyde (HTPB+GA) decomposes at lower temperature than conventional HTPB (HTPB+IPDI). The initial decomposition temperature of HTPB-GA (101℃-138℃) is lower than HTPB+IPDI about 219℃. The experimental results show that the regression rate of HTPB+GA is higher than HTPB+IPDI, 20% at Gox = 350 kg/m^2 s and 120% at Gox = 200 kg/m^2 s. The analysis results of combustion images show that HTPB-GA softens and melts at low temperature, so that the softening and melting surface and subsurface collapse in the period of combustion. The results verified the weaken bond concept is correct to modify the regression rate of HTPB based SDFs.

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